Assessing the Technology Needs of Unconventional and Marginal Resources

Phase I: The Greater Green and Wind River basins

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Executive Summary

One of the most difficult challenges in designing a natural gas exploration and production research and development (R&D) program is quantifying the potential benefits associated with a particular suite of research projects. Understanding and estimating how the development of a new technology will affect the recovery of a particular segment of the nation's gas resource requires sophisticated computer models accessing a highly-detailed characterization of the resource. The better our models and characterizations become, the better our ability to relate specific technology advancements to specific quantities of new resources, increases in productivity, or reductions in operating costs. This ability is important when making decisions about how to spend research dollars, whether public or private.

The goal of the Department of Energy's natural gas program is to assure the long-term sustainability of affordable domestic natural gas supply through a steady expansion of the nation's economically-recoverable gas resource base. To do this, the National Energy Technology Laboratory's Strategic Center for Natural Gas implements a portfolio of R&D projects designed to enable and accelerate the transition of unconventional and marginal resources into recoverable resources, and ultimately, into reserves.

In response to recommendations presented by the National Petroleum Council in their 1999 report, *"Meeting the Challenges of the Nation's Growing Natural Gas Demand"* the National Energy Technology Laboratory has undertaken a coordinated program combining resource assessment, industry tracking, and technology modeling. The assessment work is unique in that it is focused primarily on resources that are currently sub-economic and unrecoverable and uses a log-based, gas-in-place approach with an unprecedented level of geographic and stratigraphic detail. Over ten thousand uniquely characterized cells that reflect the natural variety of key geologic and engineering parameters have been established.

The first phase of this effort has focused on the Greater Green River and Wind River basins of the Rocky Mountains. These basins contain the vast majority of the total low-permeability sandstone resource for the Rocky Mountain region based on a series of past gas-in-place resource assessments conducted for the Department of Energy by the United States Geological Survey (USGS).

Results from this current effort confirm past accounts of vast volumes of natural gas existing in these two basins. In the Greater Green River and Wind River basins, over 3,600 Trillion cubic feet (Tcf) and 1,100 Tcf of gas, respectively, was determined to be remaining in place. In light of these huge volumes, exploitation of these resources will require the development and application of advanced exploration, drilling, completion, stimulation, and production technologies in order to produce gas economically and at reasonable prices.

Using the nation's most sophisticated tool for modeling the impacts of technology on a national scale, the Gas Systems Analysis Model, analyses were conducted to estimate the amount of gas in place that is technically and economically recoverable with current technologies. Roughly 10% of the gas in place in the Greater Green River and Wind River basins (360 Tcf and 120 Tcf, respectively), was determined to be recoverable. GSAM's estimates significantly exceed those of the USGS (2002) and other organizations, with the difference a result of alternative methodologies, assumptions, and geologic models designed to serve different purposes. USGS estimates are based on extrapolation of current conditions and serve as a basis for predicting the productivity that can expected from select resource elements. In contrast, GSAM estimates what could happen if the entire resource was fully developed using the most current technology as a baseline for identifying the most promising R&D avenues. When calculating a quantity as uncertain as undiscovered recoverable natural gas resource, such differences are to be expected and even encouraged, as they lead to further scientific investigation and interagency cooperation that increases the state of knowledge about our Nation's energy resources.

A key finding of this work is a documentation of the sensitivity of resource recoverability to both technology and price. Our preliminary findings indicate that roughly 11% of the technically recoverable resource is economically recoverable at $2.00/Mcf well head gas price; expanding to 28% economically recoverable at $3.50/Mcf price. Technology sensitivity analyses show that modest reductions in drilling costs or gains in recovery efficiency, which should be obtainable with continued advances in technology, lead to appreciable gains in the recoverable resource. With major technological advances, which could be obtained with an aggressive R&D program, significant amounts of gas in place could be added to the economically recoverable resource base.

This report's findings are also highly relevant to the issue of federal land use policy. Using information available from the Energy Policy and Conservation Act Interagency Team for the Greater Green River Basin, our analysis indicates that roughly 10 percent of the total gas-in-place is off limits for development due to federal land access restrictions. Timing restrictions that reduce the drilling window and could therefore increase drilling costs impact 45 percent of the total gas-in-place resource. Less than half (45%) of the gas in place in these basins is subject to standard lease terms.

This report provides critical data that will be used internally by Department of Energy planners to support project selection and other programmatic activities. History shows that Federal R&D has significant benefit in developing oil and gas in the U.S., especially those resources that are marginally economic. It is imperative that all stakeholders come together to formulate and implement environmentally sound and economically feasible development of this most important supply of clean burning, domestic energy. Phase 2 of this effort, which focuses on the Anadarko Basin in Oklahoma and the Uinta Basin in Utah, began in October, 2002.

1. Background

In 2001, the National Energy Technology Laboratory (NETL) launched a comprehensive program to assess the long-term sustainability of domestic natural gas supply in the United States. This effort has integrated pre-existing NETL activities of resource characterization and national modeling of natural gas exploration and production technologies to provide a better understanding of three key issues impacting long-term gas supply:

- The size and nature of underutilized gas resources that will be critical to future supply,
- The potential of technology to accelerate the conversion of "unrecoverable" and sub-economic resources into economically-recoverable resources, and
- The volume and nature of resources present on Federal Lands.

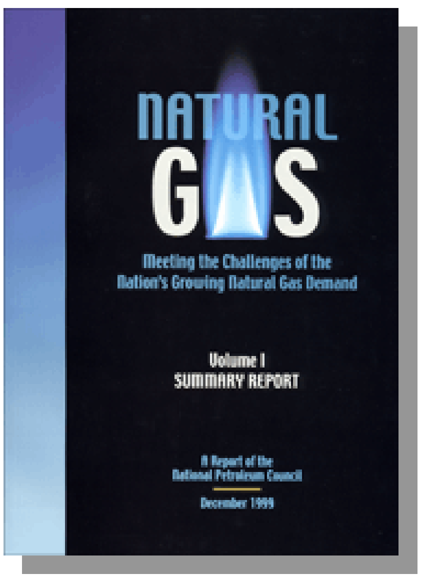

Figure 1*: The NPC's 1999 report is a major inspiration for this study*

This effort is largely in response to recommendations presented by the National Petroleum Council (NPC) in their 1999 report, *"Meeting the Challenges of the Nation's Growing Natural Gas Demand".* The NPC's recommendations concerning gas supply include the following: 1) *"Establish a balanced, long-term approach to responsibly developing the nation's natural gas resource base",* and, 2) *"Drive research and technology at a rapid pace".* These recommendations specifically noted the benefits of 1) improved knowledge of the size and nature of the resource base, 2) an accurate inventory of resources in the Rocky Mountain region and the impact of federal land access restrictions on them, and 3) efforts to define and prioritize R&D opportunities that will expand the resource potential of both producing and unexplored areas. The NPC stated, *"Particular consideration should be given to long-term technology needs for ultra-deep water, low permeability, and non-conventional reservoirs that will contribute more of the nation's gas supply in the future."*

The U.S. Department of Energy shares NPC's view. Over the coming decades, the nation is counting on the expanded use of domestic natural gas to meet critical economic, environmental, and national security goals. Clearly, technology-driven resource expansion will be the key to ensuring adequate supplies of gas. This expansion will occur through both 1) incremental technology advance that steadily increases the recoverability of the known resource base, and 2) technological leaps forward that result in the addition of vast resources that were previously unknown, overlooked, or undervalued. For more information on the background for this effort, please visit our website at http://www.netl.doe.gov/scng/explore/resource/green-river.html.

Natural Gas Technology Modeling

In 1990, NETL commissioned the creation of the Gas Systems Analysis Model (GSAM – see separate GSAM Fact Sheet included on this CD). GSAM serves as a quick-turnaround tool for scoping the national gas production, transmission, and utilization system. Analyses conducted with GSAM provide high-level insight into the relative benefit of a large variety of alternative R&D and policy scenarios. Improvements in GSAM for this purpose are ongoing, including an effort to fully integrate GSAM with the DOE's similar model for oil, *TORIS*.

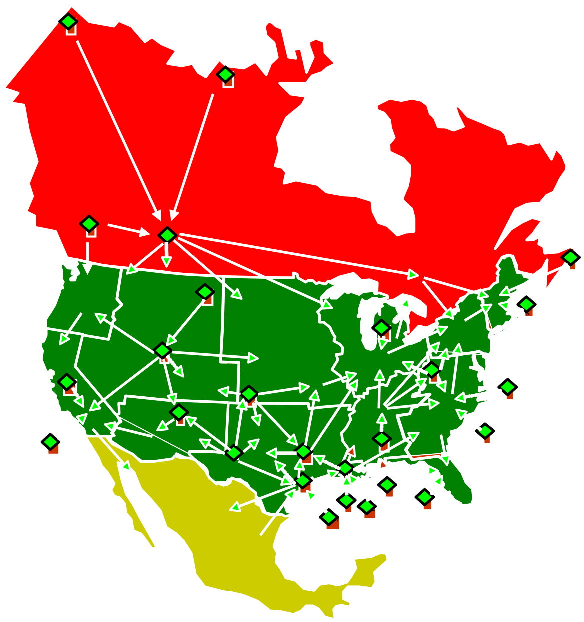

Figure 2: *NETL's Gas Systems Analysis Model (GSAM) models the supply and use of natural gas throughout North America. It is the nation's most sophisticated tool for modeling the impacts of technology.*

In assessing the priorities for its specific program in upstream natural gas exploration and production R&D, NETL is requiring GSAM to provide meaningful results at scales below the national level. Specific analyses of key regions and resource segments are increasingly needed. To meet this goal, the following capabilities are required:

- *Appropriate Modeling Logic and Algorithms*: Detailed analyses with GSAM require enhancements to the code to appropriately account for the circumstances particular to specific regions and resources; for example, the significant differences between conventional and unconventional accumulations or intra-regional variations in drilling costs

- *Appropriate Input Assumptions*. GSAM assesses resource productivity and economics relative to baseline assumptions on a variety of parameters, including drilling, completion, stimulation, and operating/maintenance costs, drilling and other infrastructure capacities, tax and royalty structures, current technical capacity, and others. These data need to capture a true picture of the current state of the industry.

- *Appropriate Resource Characterization*: The model must work with the best possible description of the nation's resources. Specifically, and in relation to the scale of the analysis being attempted, the database must…

    ✓ *Be detailed.* Increased disaggregation of the resource into a larger number of uniquely-defined segments will allow GSAM to more sensitively probe the "response" of the resource to alternative, individual R&D cases. In addition, detailed geographic disaggregation of the resource will provide an improved means to assess the impact of various federal land access stipulations, pipeline availability, and environmental policies on future supplies.

- ✓ *Be comprehensive*. The dataset must include as much of the total resource as possible. It is not appropriate to model the role of technology using datasets that already assume a certain level of technological progress. For example, a dataset for unconventional resources built around estimates of the present technically-recoverable portion will dismiss the vast bulk of the total resource out-of-hand and in particular, the very resources that aggressive R&D programs will target.

- ✓ *Address Reservoir Producibility.* To estimate the recoverability and economics of resources under a variety of future cost/technology scenarios, the model's dataset must contain estimates of permeability.

An Integrated Approach

Based upon review of its modeling needs and current modeling capacity, NETL has determined that significant improvements in both the models and the data feeding the models are warranted and could best be accomplished through the full integration of two long-standing NETL activities: resource-reserve assessment and national modeling of E&P technologies. Integration of these efforts will ensure that data is collected with the needs of the models in mind and that the models are configured to appropriately treat resource elements of particular interest. The remainder of this report describes NETL's efforts to improve its modeling databases through the direct analyses of geologic data in high-priority regions. In addition, a new activity in industry technology tracking has been initiated as a means of providing ground truth to many of the assumptions on technology utilization and impact that are incorporated into modeling base cases.

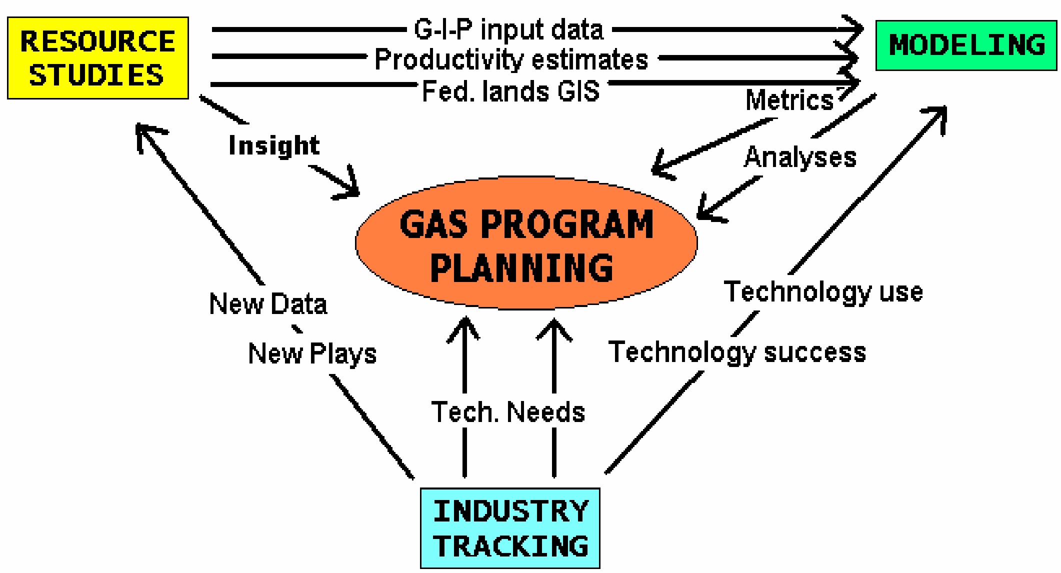

Figure 3: *Schematic of SCNG's integrated approach for planning natural gas R&D to meet the challenge of sustaining long-term domestic gas supply. This new integrated program is designed to assure that NETLs models have appropriate input datasets and logic to allow confident modeling of the role and impact of advanced technologies.*

Selection of Study Areas

The initial studies in this effort focus on deep, unconventional resources in the Rocky Mountain region. This focus is based on the understanding that gas resources in the Rockies are 1) enormous and 2) located almost exclusively on federal lands, and is responsive to the NPC's specific recommendation that the federal government work to assess the long-term natural gas supply potential of the Rocky Mountain region.

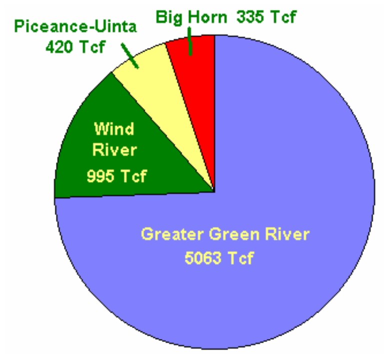

Figure 4: *Overview of the results of USGS gas-in-place assessments in four key Rocky Mountain basins.*

Within the Rockies, the Greater Green River and Wind River basins are selected as the targets for Phase I of this effort. This decision is based on several factors. First, based on a series of gas-in-place assessments conducted by the United States Geological Survey (USGS), these basins are expected to contain the vast majority of the total low-permeability gas resource for the Rocky Mountain region (Figure 4). Second, 15 years have passed since the USGS's landmark 1987 Greater Green River Basin gas-in-place study, providing ample new data. Third, the vast majority of the gas resources in these basins are currently not expected to be technically-recoverable given business-as-usual technology advances (Table 1). For example, as part of their 1995 National Assessment of the nation's technically-recoverable gas resources, the USGS assigned only 119 Tcf of resource to the low-permeability plays of the Greater Green River Basin. Low-permeability gas resources in the Wind River basin were not included in the National Assessment. Comparison of the National Assessment estimates to the separate gas-in-place estimates suggests that 98% of the gas believed to exist within these two basins, roughly 6,000 Tcf of gas, is either unassessed or deemed not "technically recoverable". This enormous untapped potential is one of the key targets of DOE R&D programs. If only 10% of this resource can be accessed, the resulting 600 Tcf of domestic gas supply would provide enormous benefits to the nation's economy, environment, and national security. However, to assess the nature and potential of new technological breakthroughs to expand access to this resource, we need to know as much as possible about the nature and conditions of *all* the resource present.

Table 1: *Overview of the results of USGS gas-in-place assessments in the Greater Green River and Wind River basins illustrating the vast resource currently deemed unrecoverable.*

Greater Green River Basin			Wind River Basin		
Play	*GIP ('89)*	*Tech. Rec. ('95)*	*Play*	*GIP ('96)*	*Tech. Rec. ('95)*
Ft. Union	96	1	Ft. Union	101	Not Assessed
Fox Hills/Lance	707	10	Lance	365	Not Assessed
Lewis	610	19	Meeteetsee	124	Not Assessed
Mesaverde	3,347	52	Mesaverde/Fales Ss.	203	Not Assessed
Frontier-Cloverly	304	37	Cody Sh.	51	Not Assessed
			Frontier	151	Not Assessed
Total	**5,064**	**119**	**Total**	**995**	Not Assessed

2. Project Methodology

The geologic analysis differs fundamentally from previous resource assessment work supported by NETL that were designed to quantify either 1) the gas-in-place with no regard to recoverability, or 2) the recoverable resource present under a single, given set of conditions. In contrast, this work attempts to produce a dataset from which recoverable resources can be reasonably appraised under a wide variety of as-yet-undefined future conditions. Consequently, this effort uses a log-based, gas-in-place approach with an unprecedented level of geographic and stratigraphic detail. Detailed disaggregation of the resource into thousands of uniquely characterized segments that reflect the natural variety in key geologic and engineering parameters is achieved through the analysis of hundreds of well log suites. Further specifics of methodology are provided in Figure 5 and below. A full archive of maps and cross-sections are available elsewhere on this CD.

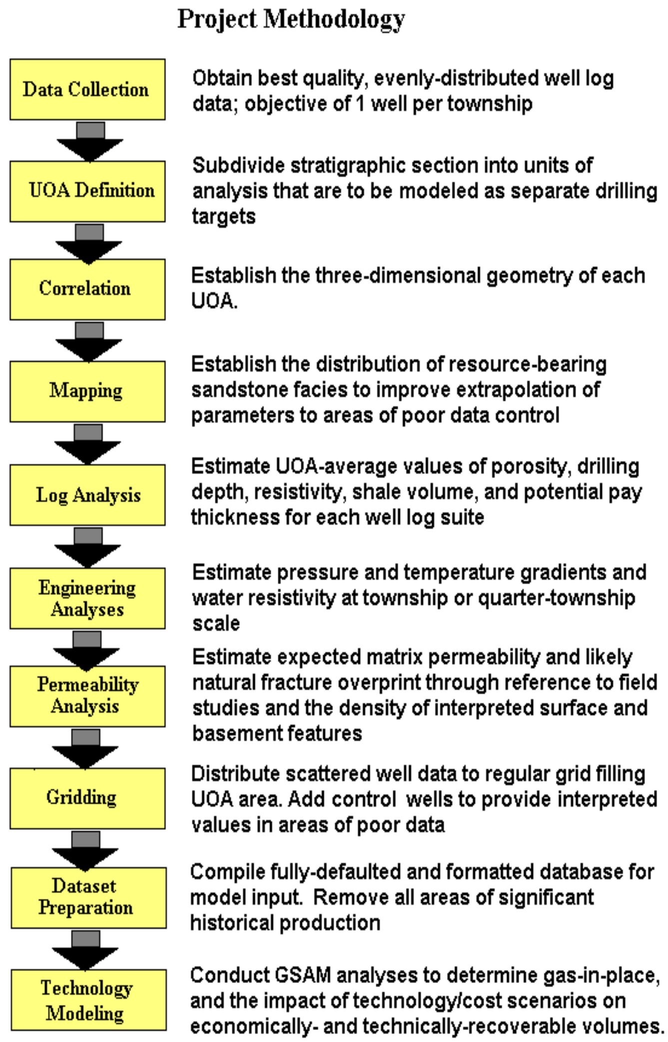

Figure 5: *Overview of project methodology.*

The Units of Analysis

The assessment of two basins, particularly two of the size of the GGRB and WRB, presented a significant challenge. Because these basins are large and contain thick, gas-charged, sedimentary sequences, the initial step was to determine which particular sections to study.

Based on the USGS's previous work, our study began with a review of the Cretaceous and older geologic section in both basins with the goal of identifying plays that 1) encompass the majority of each basin's underutilized resources, 2) are dominated by deep and/or unconventional accumulations that are the targets of DOE R&D programs, and 3) could be accomplished using a log-based methodology. This initial review settled on the following intervals of interest (Figure 6):

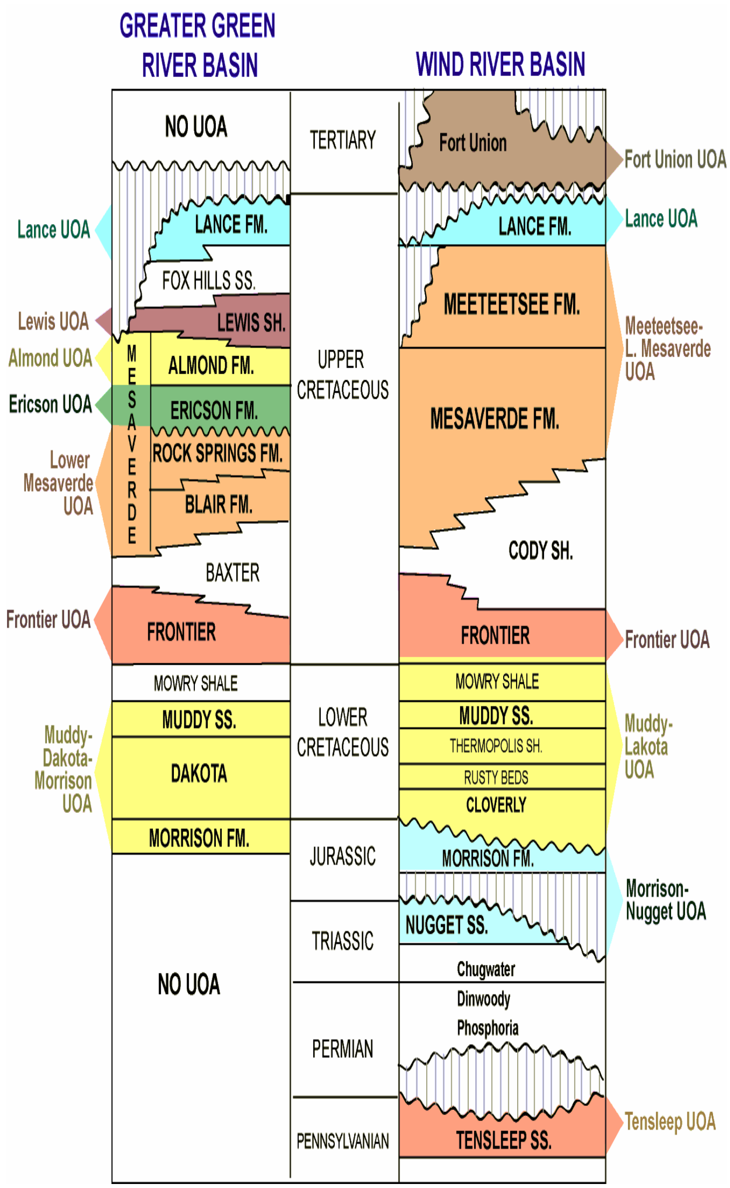

Figure 6: *Stratigraphic chart showing the subject intervals of the GGRB and WRB.*

- *Greater Green River Basin:* The entirety of the section from the top of the Lance formation to the base of sandstones within the Morrison Formation, excluding the Fox Hills sandstone and various stray sandstones within the Cody-Baxter-Hilliard-Steele shale.

- *Wind River Basin:* The entirety of the section from the top of the Lower Ft. Union formation to the Tensleep Sandstone, excluding sandstones within the Cody Shale and the interval from the base of the Nugget Sandstone to the top of the Tensleep.

With target sections established, the next step was to subdivide these intervals into "units of analysis" (UOAs); packets of resource, similar to the concept of a play, that exist in a common geologic condition. More specifically, each UOA is a package of resource that is most appropriate to characterize within the model as the target of individual wells. For example, we could not split apart units that are most likely to be ultimately completed together – doing so would require GSAM to burden each resource with the cost of individual wells. Similarly, we needed to avoid the lumping together of resources that will most likely be produced from separate boreholes. Otherwise, GSAM will calculate overoptimistic economics by assuming that the entire resource can be accessed for the cost of drilling a single well. The final Units of Analyses for the project are outlined in Figures 7 and 8 and described below.

- The *Lance UOA* is comprised of individual and amalgamated fluvial sandstones, and interbedded siltstones, shales and coals of the Lance formation. In the western GGRB where the Fox Hills-Lewis Shale sequences do not occur, the base of the Lance UOA coincides with the horizon equivalent to the point of maximum eastward transgression of the Lewis shale lithology (the top of the Almond UOA). In the central and eastern GGRB, the base of the

Lance UOA is picked at the top of the last coarsening upwards sandstone of the Fox Hills. Top of the Lance UOA was picked at the Cretaceous-Tertiary unconformity between the Lance Formation and Fort Union Formation throughout the GGRB. Given the similar depositional nature of these two continental-fluvial formations, published tops for the Lance formation were used as type sections, and for correlating throughout the GGRB.

- The *Lewis UOA* includes sandstones of two distinct types: 1) clean, coarsening-upwards sandstones interpreted as shallow-water delta-front deposits and 2) thick, vertically-stacked sequences of thinly-bedded and shale-rich sandstones interpreted to represent toe-of-slope turbidites. The shallower-water sandstones occur primarily in the Red Desert basin, but also elsewhere on the periphery of the Lewis Shale lithosome. These units represent extensions of the Fox Hills lithology that have been isolated within the Lewis Shale by significant subsequent transgression. Similar sandstones that are closely overlain by the lenticular sandstone and coal sequences of the Lance Formation are assigned to the Fox Hills Sandstone. Deep water Lewis sandstones are most common in the area between the Wamsutter and Cherokee arches.

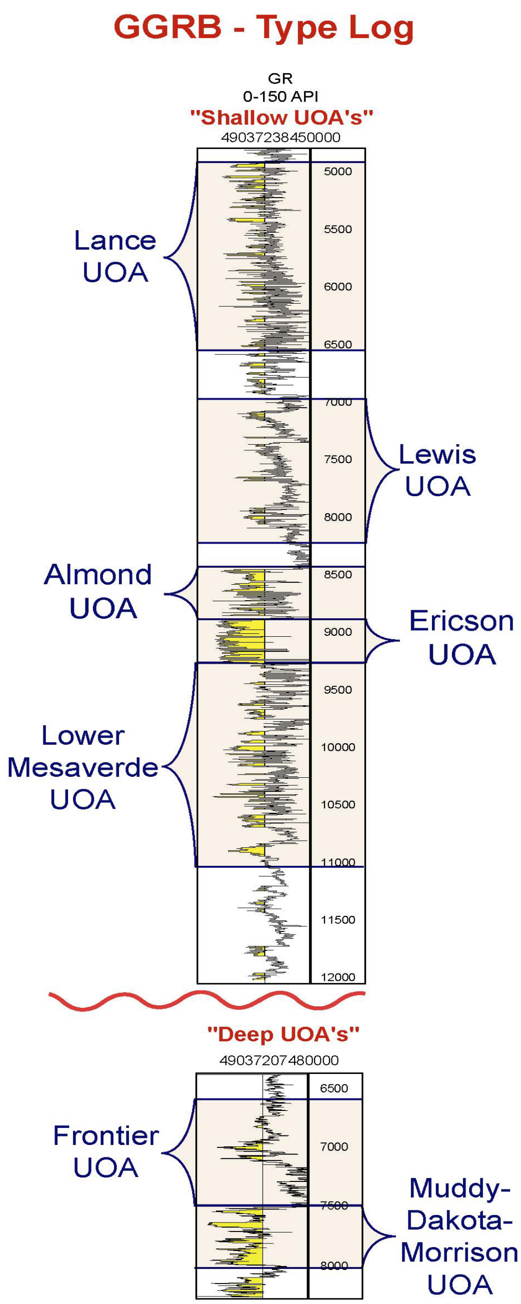

Figure 7: *Type log for the Greater Green River Basin showing UOAs*

In the past, the entirety of the Mesaverde interval has commonly been assessed together. This practice is not suitable because industry has not, and probably will not, target this entire interval with individual wells due to its large stratigraphic thickness. A review of industry practice in the basins east of the Rock Springs uplift indicated that the vast majority of Almond completions are from wells that drill no deeper than the Ericson, with the most of these terminating within the "Main" Almond section. As a result, the Mesaverde interval is divided into three UOAs that we designate as Almond, Ericson, and Lower Mesaverde.

- The *Almond UOA* includes sandstones of two distinct facies. First are the clean, blocky and coarsening-upwards sandstones (commonly referred to as "Upper Almond") marking the transgressive migration of shorelines westward at the top of the Mesaverde Group. Second are the subjacent thinly bedded and highly lenticular lower delta plain sandstones that are interbedded with coals and shales ("Main Almond"). The base of the Almond UOA is marked at the level where sandstones transition into the cleaner and more amalgamated sandstone facies typical of the Ericson UOA. The top of the Almond is clearly marked by the appearance of the Lewis Shale to the east of the Rock Springs Uplift. To the west of the Rock Springs Uplift, the top of the Almond is placed at the interpreted time-equivalent horizon with the maxima of eastward Lewis Shale migration.

- The *Ericson UOA* includes massive, quartz-rich (low radioactivity), and amalgamated fluvial sandstones (Ericson Formation) that commonly occur at the stratigraphic level of the maxima of Mesaverde progradation. The base of the Ericson UOA is clearly marked by the abrupt, commonly disconformable transition to the "dirty" sandstones, coals, and shales of the Lower Mesaverde UOA.

- The *Lower Mesaverde UOA* encompasses two distinct lithofacies. At the base are thick, coarsening-upwards sequences of sandstone (Blair Formation, etc.) associated with the eastward regression of Mesaverde environments into the Cretaceous Interior Seaway. Above is a thick section of highly-lenticular fluvial sandstones and shales of various formations (most notably the Rock Springs) within the sub-Ericson Mesaverde.

Similar to the Mesaverde units, the Frontier through Dakota interval has commonly been assessed previously as one unit. However, based on an analysis of industry drilling and completion practices in the 5 most heavily-drilled GGRB townships, operators have tended to complete either the Frontier or the Dakota individually. Multiple completions are relatively rare (Table 2). Consequently, separate UOAs for the Frontier sands and the deeper Muddy, Dakota, and Morrison sands were analyzed.

Table 2: *Historical drilling completion practices, per well, for the Frontier, Muddy, Dakota, and Morrison formations in the Greater Green River Basin. Townships selected based on number of wells drilled and completed.*

	Single Completions	Recompletions within 6 mos.	Recompletions at least 6 mos. apart	Total number of wells
T27 R113	140 (77%)	28 (16%)	13 (7%)	181
T21 R112	92 (94%)	6 (6%)	0	98
T20 R112	80 (65%)	18 (15%)	24 (20%)	122
T18 R112	65 (48%)	36 (26%)	35 (26%)	136
T23 R103	31 (57%)	17 (32%)	6 (11%)	54
AVERAGE	**68%**	**19%**	**16%**	

- The *Frontier UOA* includes all five benches of the Lower Cretaceous Frontier sandstones as well as any sands that appear within the Mowry shale interval. The top of the Frontier UOA is extended upward to include all sub-Cody Shale sandstones. The majority of the sandstones in the Frontier UOA exhibit very distinctive coarsening-upwards log signatures that are interpreted to reflect progradation of near shore environments such as river/distributary mouth bars. However, the uppermost Frontier sandstone exhibits a fining-upward signature suggestive of fluvial sedimentation.

- The *Dakota UOA* includes the Muddy sandstone, the Dakota sandstone, and sands within the Morrison Formation (Figure 1-type log). These sandstones are interpreted to represent deposition during fluvial-dominated sedimentation. In the Muddy interval, some thick, clean sandstones suggestive of incised valley-fill are noted. The base of the UOA is marked at the lowest significant sandstone in the Morrison sequence.

Wind River basin UOAs

The uppermost intervals in the target section of the Wind River basin contain thick sequences of fluvial and lacustrine clastics of the Fort Union, Lance and Meeteetse formations. On well logs, particularly on gamma-ray logs, these units are not easily distinguishable. Published interpretations, as well as subtle variations in sandstone-shale ratio, the abundance and clustering of coals, and trends in formation conductivity, are the primary tools for correlation.

- The *Fort Union UOA* and *Lance UOA* are thick, monotonous sequences of interbedded fluvial sandstones, shales, and coals. Although the two units are lithologically very similar, combined they represent too thick a sequence to include within a single UOA. Therefore they are broken into two UOAs based on their interpreted formational contacts. The top of the Fort Union UOA is marked in large areas of the basin by the base of the Waltman Shale. The Fort Union/Lance transition was commonly traced based on previous interpretations (primarily the work of the USGS) conditioned by an attempt to place the contact at the top of a relatively sandstone-poor zone at the top of the Lance.

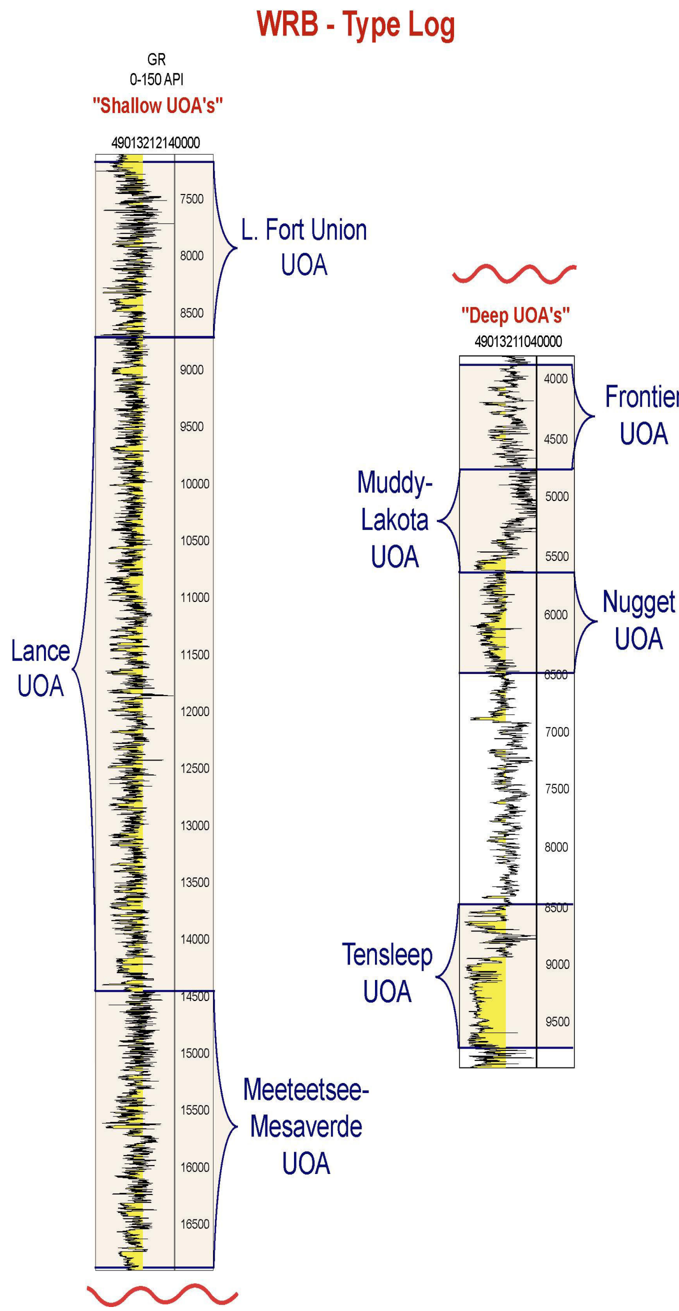

Figure 8*: Wind River basin type log showing UOAs*

- The *Meeteetsee/Mesaverde UOA* includes an array of fluvial-deltaic environments within the Meeteetsee and Mesaverde Formations. The relatively clean and thick Teapot sandstone lies at approximately the middle of the UOA. The upper contact of the unit is placed at the base of the initial sequence of thick fluvial sandstones thought to mark the base of the Lance Formation. The UOA extends down section to the top of the first significant shale within the Cody Shale. Sandstones within the Cody, such as the Shannon and Sussex, are not included.

- The *Frontier UOA* includes the distinctive coarsening-upwards parallic sandstones of the Frontier Formation. The uppermost boundary of the UOA climbs stratigraphically upsection as traced to the east. The lower limit of the UOA is placed at conspicuous and highly radioactive shale marking the top the Mowry shale. This shale most likely represents a sea-level highstand (maximum flooding surface) that proceeded progradation of the Frontier units.

- The *Muddy-Lakota UOA* includes sandstones within the Mowry Shale, as well as the subjacent Muddy, Dakota, and Lakota-Cloverly sandstones. The Mowry is predominantly a marine unit that contains no significant sandstones within the basin. The Muddy is locally very thick and clean, and occurs as highly-lenticular channelized sandstones. The Dakota sandstone is reported as productive in several parts of the basin, however, in this study, the unit identified as Dakota is consistently less than 5 feet in thickness. At the base of the UOA, the Lakota (Cloverly) sandstone is a highly continuous channelized conglomeratic sandstone. The base of the UOA is marked by a low-angle unconformity at the base of the Lakota unit.

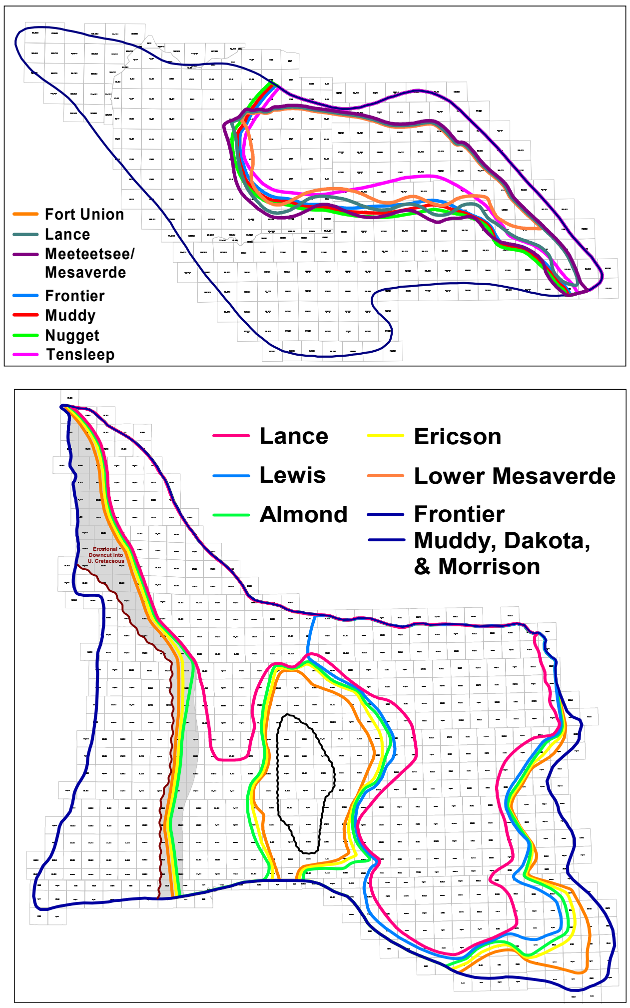

Figure 9: *Areal boundaries for UOAs in the Wind River basin.(top) and Greater Green River basin (bottom)*

- The *Nugget UOA* includes sandstones within the Morrison Formation as well as the Nugget Sandstone. On logs, the Nugget is typified by a highly-serrated and shaley character suggestive of vertical amalgamation of numerous thin sandstone beds. The base of the Nugget UOA is placed at the base of a consistent shaley zone approximately 300 feet above the Alcova limestone marker bed.

- The *Tensleep UOA* includes the thick and massive Tensleep Sandstone only. The unit produces oil almost exclusively in the basin. Only a handful of wells have penetrated the Tensleep Sandstone at depths below 15,000 feet, where gas is expected to dominate.

Appraised Areas

Each UOA was appraised over the entire area in which it occurred. Ultimate location of the aerial boundaries of each UOA (Figure 9) was later restricted to include only 1) areas with drilling depths of at least 5,000 feet (to exclude shallow high-porosity sandstones that may be considered conventional); and 2) areas deemed to be gas-prone. In the Greater Green River basin, oil production is very uncommon below 5,000. However, in the Frontier and deeper UOAs in the Wind River basin, oil production is common to depths exceeding 10,000'. Consequently, the aerial limits of the Frontier, Muddy-Lakota and Nugget UOAs in the Wind River basin were set at 12,000' drilling depth. The limit for the Tensleep UOA is set at 15,000'. These depth cut-offs are based primarily on a review of data from I.H.S. Energy Data (see Table 3). Finally, note that in many prior assessments, the appraised area has been limited to overpressured areas. However, because this study subdivides each UOA into a large number of geographic cells each with a unique mid-point pressure, no such limitation was necessary.

Table 3: *% of total completions as oil well completions for Deep UOAs (data from I.H.S. Energy Data)*

	GGRB		WRB			
Depth	Frontier	Dakota	Frontier	Mud.-Lak. *	Nugget	Tensleep
6000-7999	1%	19%	86%	35%	100%	100%
8000-9999	3%	6%	8%	89%	100%	100%
10000-11999	3%	20%	33%	52%	0%	100%
12000-13999	0%	5%	0%	100%	0%	100%
14000+	0%	0%	0%	0%		

** includes only completions of the Muddy and Lakota sandstones*

Data Collection

For both basins, well logs were collected with the goal of obtaining quality log suites from one or more of the deepest wells in each township. Well productivity was not considered to ensure the dataset was not biased to higher quality reservoirs. Well data were collected separately for each UOA (although many wells are used for more than one UOA), with the following guidelines:

Table 4: *Well log data density used in the study. Number of wells = total wells used in the study to support correlation and mapping. Full log suites = total wells used in determination of volumetric parameters.*

Unit of Analysis	**Number Of wells**	**Number of full Log Suites in appraised area**	**Townships in Appraised Area**	**Full Log Suites per Township**
Greater Green River Basin				
Lance	209	88	297	0.30
Lewis	399	297	169	1.76
Almond	369	293	265	1.11
Ericson	301	242	338	0.72
Lower Mesaverde	153	136	353	0.39
Frontier	266	158	489	0.32
Dakota-Morrison	192	131	467	0.28
Wind River Basin				
Fort Union	75	44	49.8	0.92
Lance	63	28	58.8	0.48
Meeteetsee-Mesaverde	60	27	67.1	0.40
Frontier	136	19	56.2	0.34
Muddy-Lakota	123	16	56.6	0.28
Nugget	95	8	55.0	0.15
Tensleep	82	4	24.8	0.06

- Fullest possible penetration of UOA
- Even geographic distribution of data points
- Full and quality log suite, including:
  - Caliper Log (for determination of reliability of porosity data)
  - Gamma-ray well log (for determination of Vsh)
  - Compensated Density Porosity Log (for determination of porosity and potential pay)
  - Induction Log (for determination of shale and formation resistivity)

As expected, the density of quality log data is best for the shallower target intervals. Exceptions include the Lance in the GGRB, which contains many penetrations, but because the targets of these wells were typically deeper formations, full logging suites are relatively rare. In all UOAs, a large number of additional well logs (either lacking full suites or occurring in shallow or oil-prone areas), were used to support correlation and mapping. The poor data density obtained for the Nugget and Tensleep formations in the Wind River basin (particularly at the target depths) precluded further analysis of resources using this methodology. Maps prepared for these intervals using the total well log database are provided.

Correlation

With log data in hand, each UOA was correlated in loop fashion to establish the occurrence and distribution of lithofacies (Figure 10). Correlation was generally lithostratigraphic, and focused on establishing the UOA boundaries. Such correlations establish intervals of consistent lithology, and commonly produce unit boundaries that cross time-lines.

Where appropriate and possible (primarily in marine and marginal-marine intervals), detailed chronostratigraphic correlation was accomplished. These correlations identify rock sequences of equivalent age without reference to lithology and are necessary for

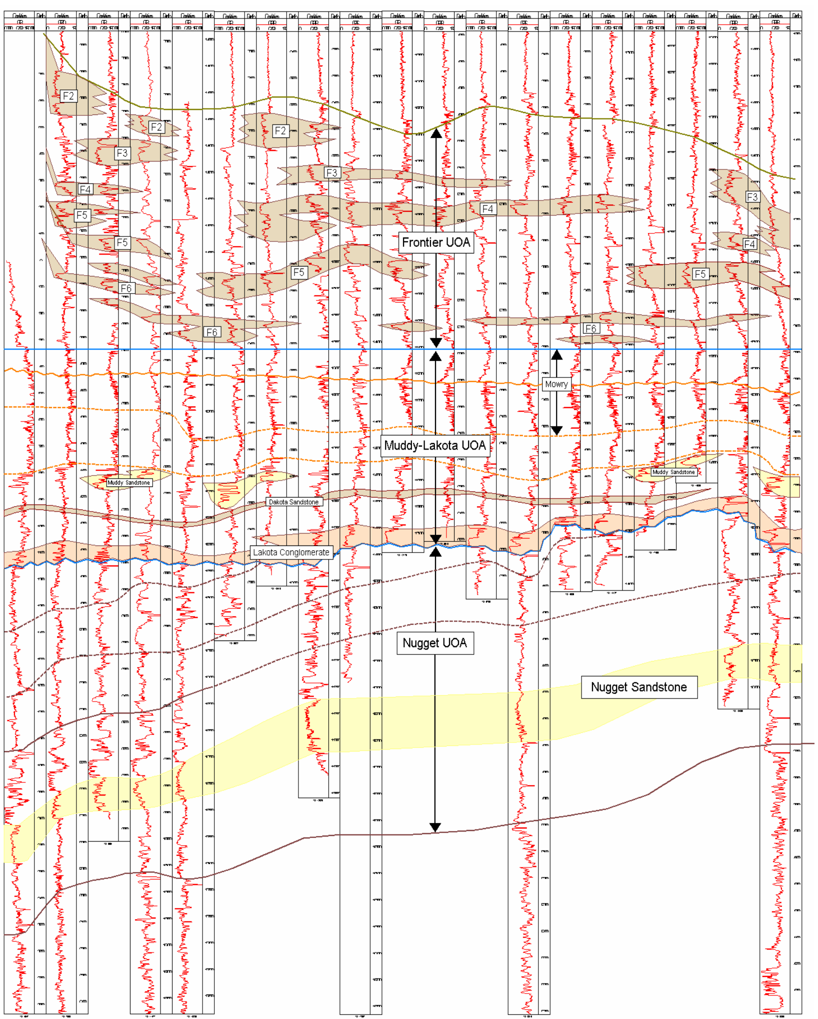

Figure 10: *W-E cross-section showing the correlation of the Frontier, Muddy-Lakota, and Nugget UOAs in the Wind River basin.*

the reconstruction of trends and geometries of depositional environments. A few key marker beds such as the highly radioactive shale ("Asquith marker") present in the lower Lewis Shale, other similar "hot" shales, as well as limestones, and bentonites closely approximate time-lines and are critical in allowing chronostratigraphic correlation. Because such key beds are generally lacking in fluvial and lacustrine facies, no detailed chronostratigraphic correlations were accomplished for the Lance, Fort Union, Lower Mesaverde or Mesaverde-Meeteetsee UOAs. In either lithostratigraphic or chronostratigraphic correlation, the methods used were tailored to the specific needs of each UOA. For example, in the Lewis and Mesaverde UOAs in the GGRB, correlation was achieved almost exclusively through comparison of gamma-ray well log signatures. Other UOAs, such as the Frontier and Dakota in the GGRB and the Fort Union and Lance in the WRB, required that gamma-ray signatures be supplemented with information from resistivity/conductivity curves and other data.

Mapping

The purpose of mapping is to provide a graphical view of the distribution of a geologic parameter. Maps were contoured by hand to allow geologic intuition gained through years of analysis of similar deposits to guide the sound extrapolation of information from areas of good data control to areas where data is lacking.

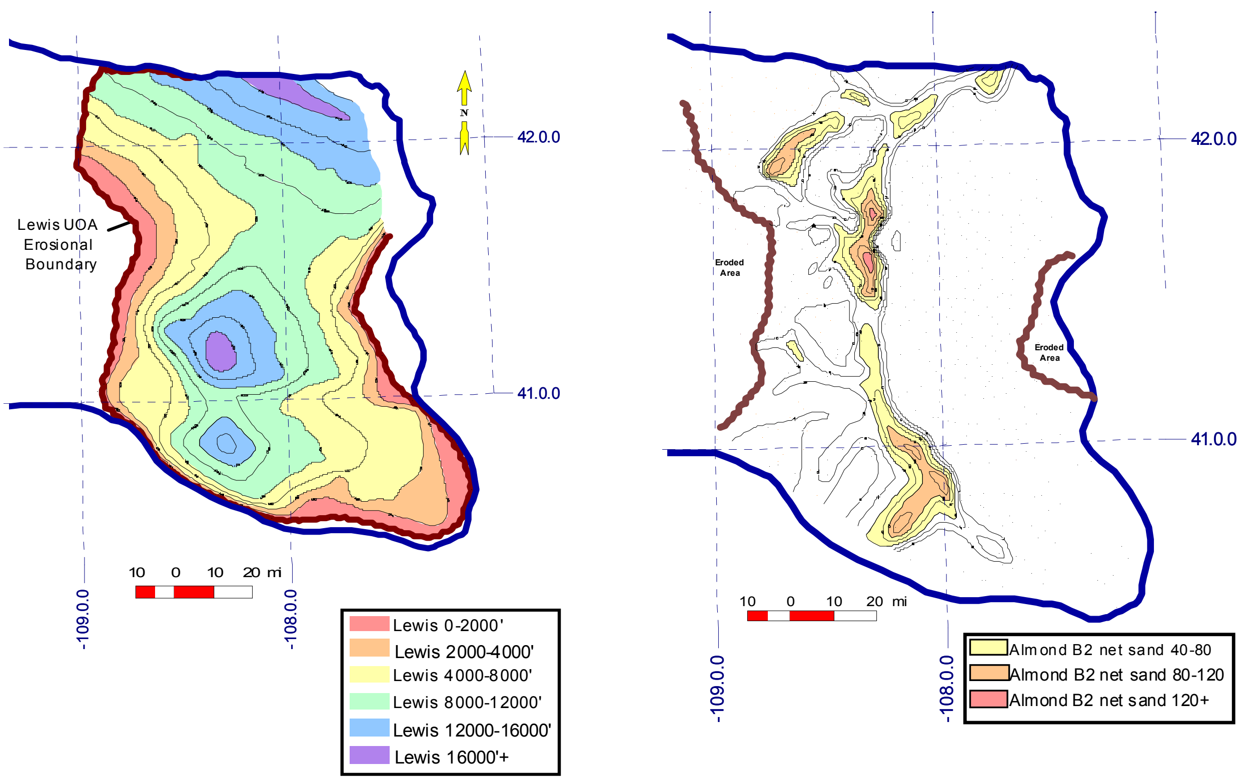

Figure 11: *Example Geologic Maps: Left - Drilling depth to mid-point of the Lewis UOA, GGRB, Sandstone isochore map for marginal-marine Almond "B2" sandstones, GGRB. A complete archive of maps and cross-sections created during this study is presented elsewhere on this CD.*

This effort has produced two basic sets of hand-contoured geologic maps. Drilling depth maps show the distance from surface to the stratigraphic mid-point of the UOA. Sandstone isopach maps (most properly – isochore maps) show the composite vertical thickness of all sandstone present within an interval. The sandstone isopach maps are based on sandstone thickness as determined through the gamma-ray base-lining method with a 50% clean-sand cut-off. The following sandstone isopach maps were created and are available elsewhere on this CD.

Greater Green River Basin

- GGRB: Lance UOA – Total sandstone thickness
- GGRB: Lewis UOA – Total sandstone thickness plus 6 interval isopachs (Lewis 8 (youngest); Lewis 7, Lewis 6, Lewis 5, Lewis 4, and Lewis 3 (oldest))
- GGRB: Almond UOA – Total sandstone thickness plus 6 interval isopachs (representing various horizons of the "Upper Almond" sandstone - Almond A (youngest and westernmost), Almond B1, Almond B2, Almond B3, Almond B4, and Almond C (oldest and easternmost)
- GGRB: Ericson UOA – Total sandstone thickness
- GGRB: Lower Mesaverde UOA – Total sandstone thickness
- GGRB: Frontier UOA – Total sandstone thickness plus 6 sandstone isopachs (Frontier 0 (youngest), Frontier 1, Frontier 2a, Frontier 2b, Frontier 3-4, Frontier 5 (oldest)).
- GGRB: Dakota UOA – Total sandstone thickness plus 3 sandstone isopachs (Muddy (youngest), Dakota, and Morrison (oldest)).

Wind River Basin

- WRB: Fort Union UOA – Total sandstone thickness
- WRB: Lance UOA – Total sandstone thickness
- WRB: Meeteetsee-Mesaverde UOA – Total sandstone thickness
- WRB: Frontier UOA – Total sandstone thickness plus 4 sandstone isopachs (Frontier 1-2 (youngest), Frontier 3, Frontier 4 and Frontier 5 (oldest))
- WRB: Muddy-Lakota UOA – Total sandstone thickness plus 2 interval isopachs (Muddy and Lakota)
- WRB: Nugget UOA – Total sandstone thickness plus 1 interval isopach (Nugget)
- WRB: Tensleep UOA – Total sandstone thickness

Log Analysis

Given a logs with UOA boundaries marked, the procedure for log analysis was as follows:

- Record drilling depth at mid point.

- Determine thickness of sandstone lithology for the purpose of mapping through baseline analysis of the gamma-ray log.

- Mark the potential pay zones through collective reference to the gamma-ray, density-neutron, resistivity, and caliper logs.

- Determine the composite average shale-volume across all the potential pay zones through analysis of the gamma-ray well log.

- Determine the average porosity in the potential pay zone through analysis of the compensated density porosity log.

- Determine the average resistivity in the potential pay zones through analysis of the resistivity log.

- Determine the shale resistivity throughout the UOA from the resistivity log.

The following, supplemented by Figure 12, describes these steps in further detail:

Drilling depth mid-point was calculated for every UOA in each well analyzed. This depth is used in the model to estimate drilling, completion, stimulation, and operating/maintenance costs.

Sandstone Thickness: To determine net sandstone thickness, sand and shale baselines were drawn for every gamma ray (GR) log analyzed. The "100% sand" baseline is a vertical line on the log indicating the reading expected for totally-shale free sandstone. Such sandstones are rare, and in many instances, the 100% sand line is drawn based on the reading exhibited by limestones where present or by assuming that the very cleanest sandstones in the section contained only a

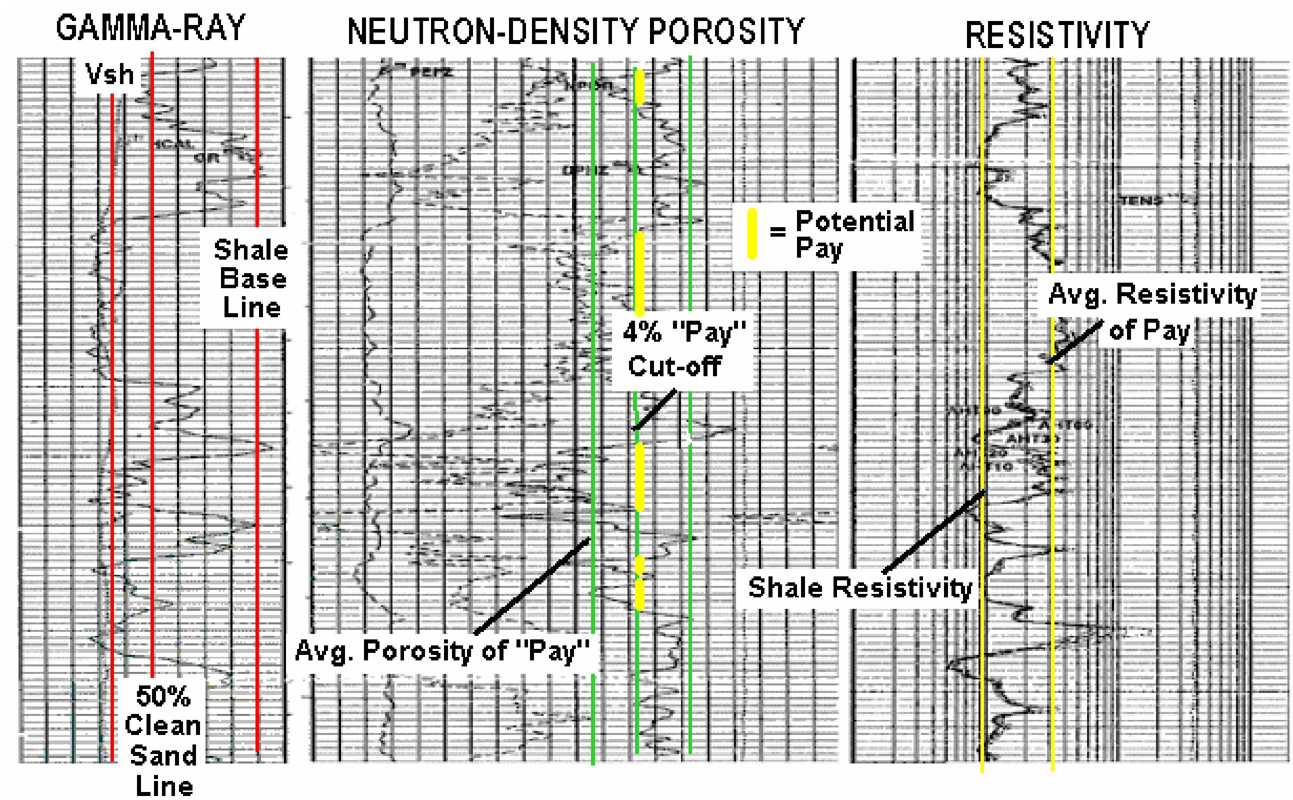

Figure 12: *Sample well log showing the key elements of the well log analysis procedure. "Potential Pay" is the thickness of interval characterized for each UOA. The average values for Vsh,, Porosity, and Resistivity are all relative to the potential pay intervals only*

minimal amount of shale (5 – 10%). The "100% shale" baseline indicates the expected GR reading for shale. The location of the shale baseline is allowed to change with depth to reflect changing hole conditions and shale lithology. (The goal is to construct baselines that reflect the contribution to total unit radioactivity of the shale likely to be incorporated into each sandstone). These two lines are bisected by the 50%-sand line. To determine total sandstone thickness, all readings to the left of the 50%-line are interpreted as sandstone. All readings to the right are siltstone or shale. GR-log baselining, like many aspects of regional resource appraisal, is not an exact science. Once a geologist has looked at several hundred logs in a region, trends can be identified that allow the baselines to be used to standardize all of the GR logs and correct the interpretations of logs that may not have been recorded optimally.

Potential Pay Thickness: A pivotal determination in the log-analysis procedure is the determination of "potential pay thickness". In general, the term "pay" is usually equated with an interval that is expected to produce under current circumstances. Geologists are accustomed to establishing practical reservoir or field-specific porosity (for example 6 or 8%) and gas saturation (commonly 60%) cut-offs in determining pay. However, the goal of this effort is to create resource descriptions that will allow a computer model to determine what segment of the total resource *might be pay* as much as 20 years into the future under cost/technology scenarios that may be very different from what currently exists. Therefore, aggressive cut-offs have been used in defining "potential pay" with the understanding that under most technology/cost conditions, the models may not consider much of this low-quality "potential pay" to be viable. Once zones are identified as "potential pay", estimates for all remaining parameters (shale volume, porosity, resistivity) were determined for these zones only.

The criteria for potential pay is as follows (note; all these conditions must be met before the unit is included as potential pay):

- Less than 75% shale volume – that is; units not counted as sandstones in the lithofacies mapping (Vsh between 50% and 75%) can still be counted as potential pay given appropriate porosity.

- Greater than 4% porosity – in practice, this criteria amounts to including all noticeable deflections from the expected porosity reading for shale.

- Greater than a set minimum thickness – isolated thin beds are not included, however, the composite thickness of a series of thin beds that form a larger unit (such as a turbidite deposit) was included.

- Less than 70% water saturation (Sw), based on our current best understanding of water resistivities.

- Adequate caliper indicating no large washouts or severe rugosity in the wellbore that would make porosity log readings unreliable.

Average Shale Volume of Potential Pay: The average shale volume (Vsh) is determined though visual inspection of the gamma-ray reading of potential pay zones relative to the gamma-ray base line. In UOAs with highly variable Vsh, weight averaging through the UOA was used.

Average Porosity of Potential Pay: An average porosity for the potential pay in each UOA was determined almost exclusively from recent vintage, full-scale (the "5-inch log"), compensated density-porosity logs. In many instances, the average porosity was taken through visual inspection of the log. Where density-neutron "cross-over" occurred, porosity is taken by the average of the two readings. Where there was no "cross-over" the density porosity log reading was used. Also, similar to gamma-ray baselining, the determination of porosity provides the geologist with the opportunity to normalize porosity data gathered from a variety of decades, tools and operators. A basic assumption is that the density porosity log should read consistently low (0 – 4%) in shale. Where log data were more erratic, a baseline was drawn through the average density porosity value in shales, and the average porosity reading was then determined by counting the deflection to the left of the baseline. Furthermore, in UOAs known to consist primarily of thin-bedded units (for example, the Lewis Shale turbidites), the porosity recorded was at the common maximum reading, and not at the visual average. This approach (which is also applied to determination of resistivity) helps to counteract the misleading log readings obtained for intervals containing numerous individual units that are thinner than the logging-tool resolution.

Average Resistivity of Potential Pay is approximated using the detailed 5" resistivity log. When large differences in resistivity occurred within one interval (e.g. 20 ohms readings for 100 feet of potential pay mixed with 200-ohm reading for another 50 feet of potential pay), resistivity was weight-averaged over the interval. However, in most instances, the value is determined by visual averaging.

Average Shale Resistivity (Rsh) across the UOA is approximated from the detailed ("5-inch") resistivity log. Shale resistivity is allowed to vary from one UOA to another in a given well. Such variation is common due to changes in formation pressure and shale lithology (for example, marine shales versus non-marine shales).

Note on Estimation of Water Saturation: Water saturation can be estimated using shaley-sand formulations (we have used the Simondoux equation) that correct total measured resistivity for water resistivity (Rw), shale volume (Vsh), and shale resistivity (Rsh). Unfortunately, the water resistivity parameter is very difficult to determine. It can only be estimated from well logs given the presence of 100% water-wet sandstones. However, due to the ubiquity of gas in basin-centered accumulations, such wet sandstones, particularly ones in close proximity to the units being analyzed, are not common. As a result, to calculate Sw, Rw must be determined from other data. For the Lewis UOA, sufficient water chemistry data was available to allow estimation of Rw. For the other UOAs, Rw's were based on experience and trial and error. We intend to revisit these calculations once ongoing NETL studies to sample and analyze Rocky Mountain region formation waters and other industry data provide better information.

Note on Parameter Averaging: The GSAM model requires that each resource package to be analyzed (each grid cell in each UOA) be given a single value for each parameter. Therefore,

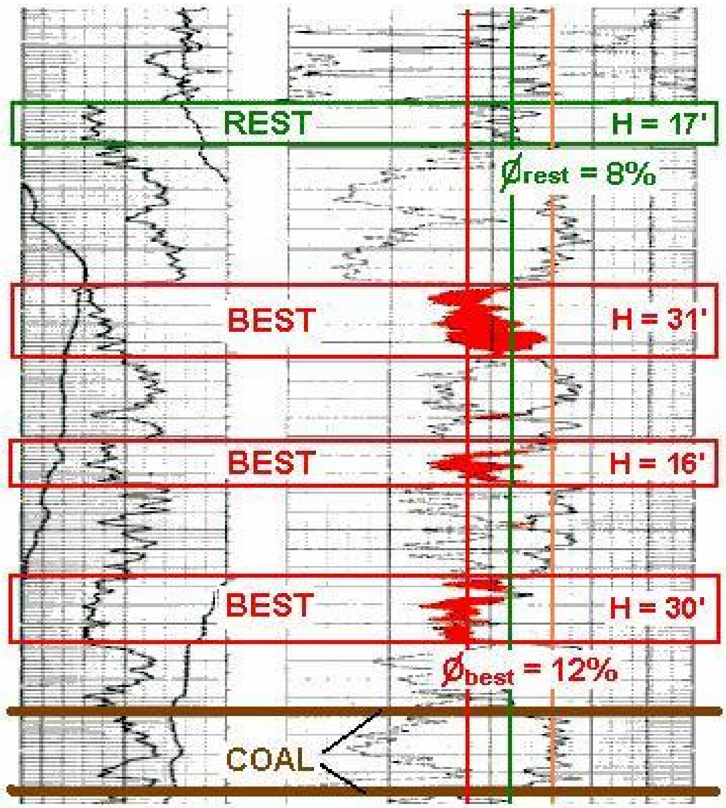

Figure 13: *Example of the use of separate 'best' and 'rest' categories in the Almond UOA.*

despite our efforts to create detailed and disaggregated datasets, it remained necessary to average parameters across large vertical sections. For many units of analysis, this averaging did not create any major difficulties, as parameters such as porosity and saturation were often fairly consistent within a unit. In many instances, the "averaging" was done visually; in others (where the parameter displayed greater variability), detailed counts were conducted and averages obtained through weight-averaging. However, for the upper Mesaverde "Almond" UOA in the GGRB, averaging of values across the high-quality marginal-marine "Upper Almond" sandstones and the numerous lower-quality "Main Almond" units was not ideal. Such averaging produces a characterization that may not appropriately describe any part of the interval. Therefore, the solution was to prepare separate characterizations of the "best" and "rest" potential pay zones within that unit (Figure 13). Included within the "best" category are zones that would be most likely to be completed (commonly those marked by density-neutron cross-over). All lower-quality potential pay is assigned to "rest".

The intention of differentiating best and rest zones in the GGRB Mesaverde (including Almond, Ericson, and Lower Mesaverde UOAs) is to provide for more precise modeling of current industry behavior, and allow the analyses of technological advances that might allow more of the potential pay to be completed. GSAM does not currently have the capacity to utilize the "best vs. rest" distinction; however modifications to the model to better handle thick sequences of stacked reservoirs of varying quality are currently in planning.

4. Engineering Analysis Methodology

The engineering analysis was designed to provide data that could not be obtained directly from well log analysis. Data obtained or estimated for each UOA at either the township or quarter-township level include 1) pressure gradient; 2) temperature gradient; 3) water resistivity; 4) matrix permeability; and 5) fracture permeability overprint.

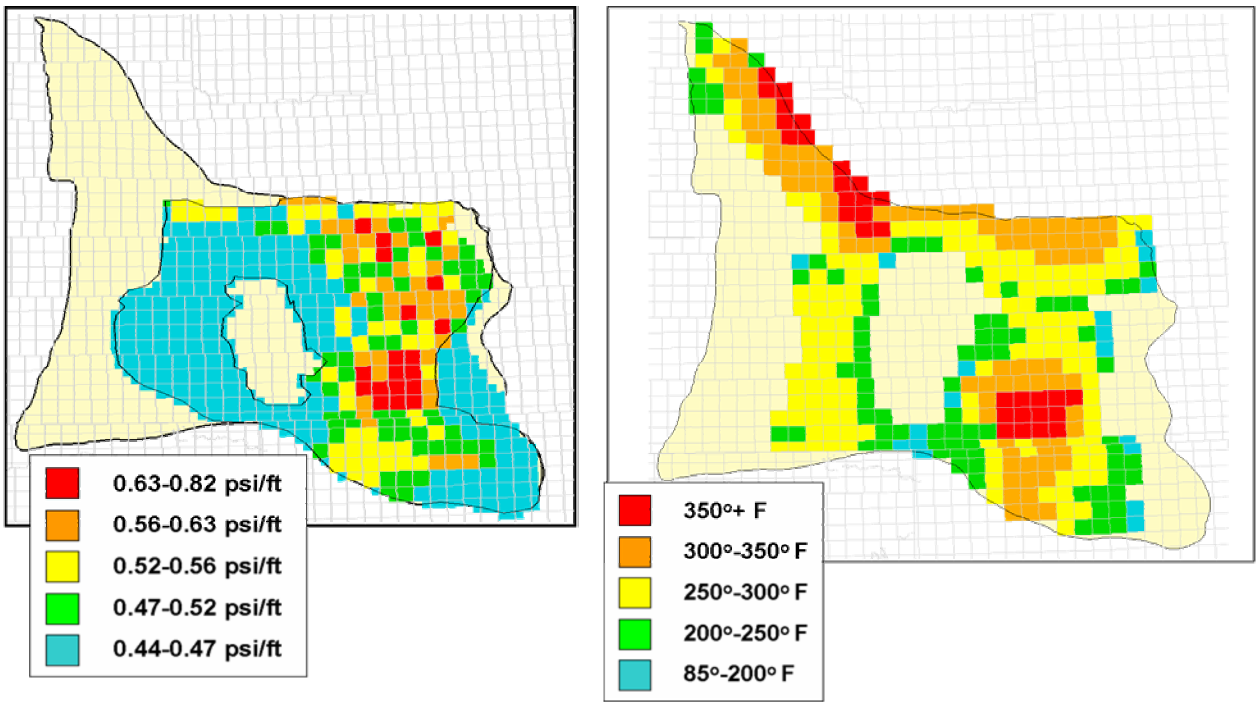

Figure 14: *Example maps of engineering parameters: Left – Reservoir pressure gradients per township for the Lower Mesaverde UOA, GGRB. Right - Reservoir temperature for the Frontier UOA, GGRB.*

Reservoir Pressure

Average reservoir pressure gradient for each UOA is based on information from previous work by Advanced Resources International in the GGRB as supplemented by new work. The data on reservoir pressure was assembled from a combination of individual pressure build-up tests on key wells supplemented by drilling mud-weight data. The mud-weight data was calibrated to actual well test data where possible. Where calibration was lacking, the conversion from mud-weight to pressure gradient was accomplished by the following: $P_{gradient}$ = Mud Weight X 0.0552. The resultant pressure gradient was then gridded throughout the study area to provide gradients at either a quarter- township or township scale. Pressure for each cell is then determined by multiplying gradient by mid-point drilling depth. This methodology provides accurate pressure estimations assuming that drilling is commonly in balance; overestimation of formation pressure may occur where drilling is typically accomplished overbalanced.

Reservoir Temperature

Temperature gradients for each UOA are based on an existing ARI databases supplemented by bottom-hole temperatures recorded on well logs. Temperature gradients were then gridded throughout each play area to provide estimates at the quarter-township or township scale. Reservoir temperature was determined for each grid cell by assuming a near surface temperature of 60 °F as follows: $T_{reservoir} = 60 + (T_{gradient} * \text{Depth})$.

Formation Water Resistivity

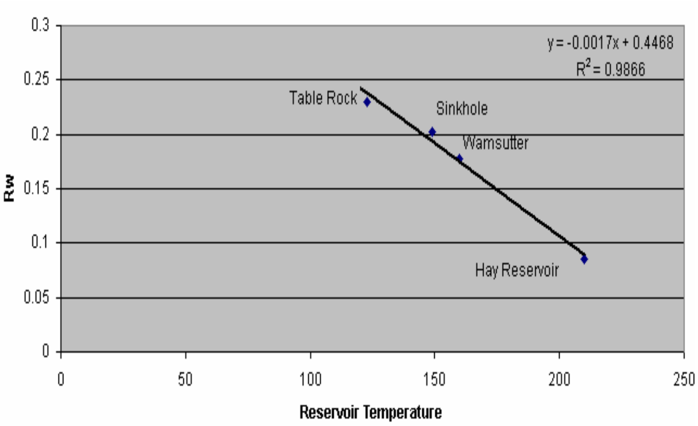

Figure 15: *A plot of four Rw values for published Lewis water analyses versus reservoir temperature*

Formation water resistivity (Rw) data are needed to determine water saturation (Sw) from well log data. Unfortunately, Rw data for both the Greater Green River and Wind River basins are highly variable and not widely available. However, for the Lewis UOA, measured Rw's from four Lewis fields were available, and were converted to subsurface conditions using Arp's equation:

$$Rw_{reservoir\ conditions} = Rw_{surface}\ X\ (T_{surface}+6.77)/T_{reservoir}+6.77)$$

These data were plotted (Figure 15) and the resultant relationship *(Rw = -0.0017T + 0.4468)* was used to estimate Rw for all cells in the Lewis UOA. Unfortunately, reliable water chemistry data was not available for the remainder of the UOAs to allow similar determination of Rw. Therefore, the data used are primarily assumptions based on limited information (Table 5). We have generally assumed higher Rw's for those UOAs that are dominantly non-marine and lower values for marine and near-shore UOAs. We have also generally assumed decreasing Rw with depth. For example, in the Frontier and Dakota UOAs in the GGRB, Rw was set to range from 0.04 for cells with the greatest drilling depths to 0.09 for those with the shallowest drilling depths.

Figure 16 illustrates the dependence of calculated Sw on Rw. This observation underscores the potential error inherent in calculating Sw from log data without reliable Rw data. However, it unlikely that this practice produces greater error than the direct assumption of Sw. Therefore, we have elected to assume Rw, note the difficulties, and calculate Sw.

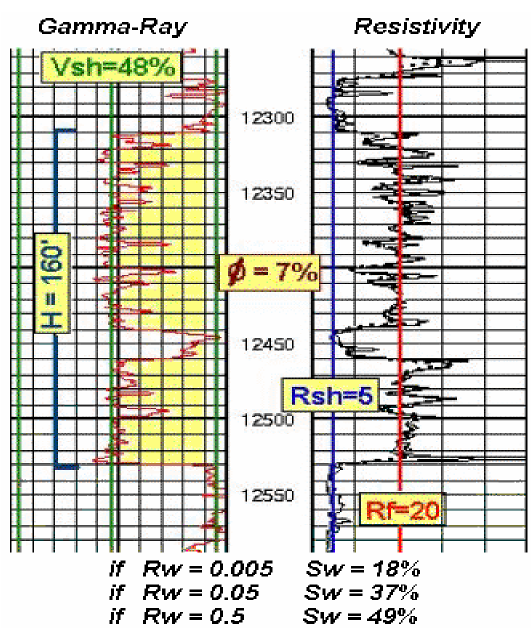

Figure 16: *A typical log from the Lewis UOA showing the impact of various Rw assumptions on calculated Sw.*

This allows us to use the observed variations in shale volume, shale resistivity, and formation resistivity to produce datasets with reasonable estimates of the regional variation in Sw. As noted above, final Sw estimates will be revised as new Rw data becomes available.

Table 5: *Water Resistivity Assumptions (Ohm-m)*

Greater Green River Basin		Wind River Basin	
Lance	0.10	Fort Union	0.40
Lewis	Variable	Lance	0.35
Almond	0.23	Meeteetsee-Mesaverde	0.25
Ericson	0.70	Frontier	0.05
Lower Mesaverde	0.23	Muddy-Lakota	0.05
Frontier	0.04-0.09	Nugget	0.05
Dakota	0.04-0.09	Tensleep	0.05

Effective Permeability

The pivotal element in providing datasets to model the future economics and productivity of these resources is an estimation of effective permeability. Although it is well known that matrix permeability in tight sandstones is commonly less than 0.01 millidarcies (md), to assume this value as the pervasive permeability for these formations would ignore the contribution of natural fracturing. Unfortunately, fracture permeability (or the overall effective permeability) is typically not reported or measured in the field. Therefore, finding a reasonable methodology to approximate the magnitude and aerial variability in effective permeability in areas that are largely unexplored is a significant challenge. Our solution for Phase I of this effort is to estimate structural complexity from remote sensing data, correlate that information to permeability in areas where data is present, and then estimate permeability in each grid cell of each UOA through the extrapolation of these data.

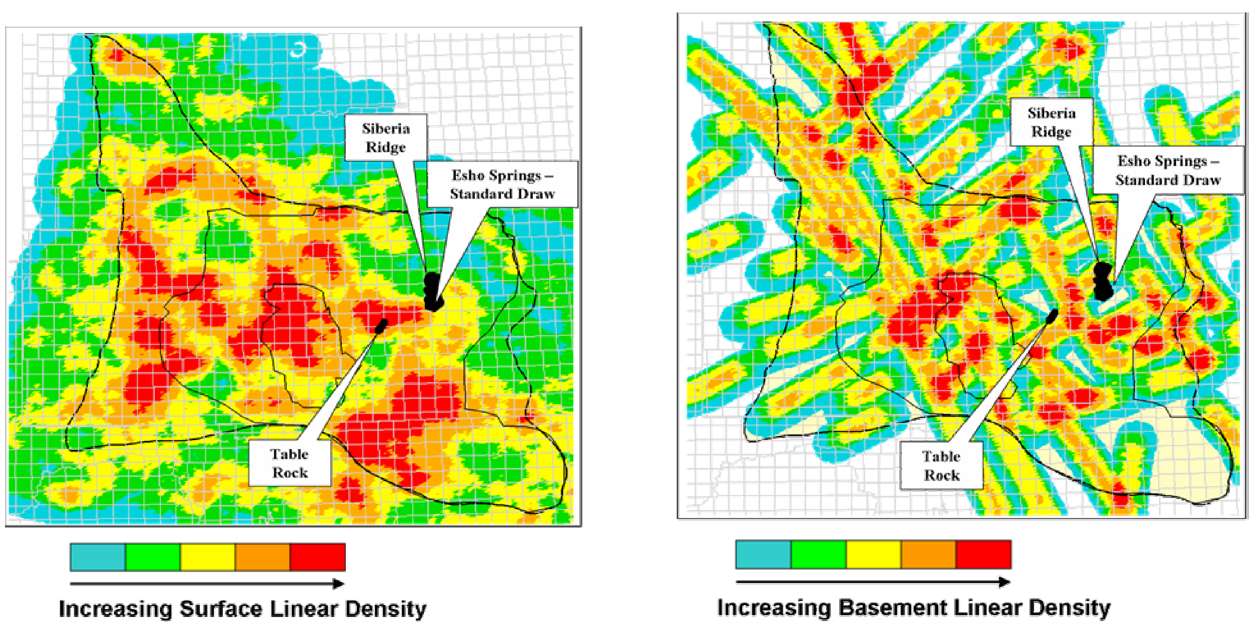

Figure 17: *Two components in the calculation of structural complexity. Right: Basement component as determined from remote sensing data (magnetic and gravity): Left: Surface component based on density of mapped surface lineaments.*

Structural Complexity: The structural complexity for each township was based on a combination of two sets of information. Mapped surface lineaments are used to determine density of surface features. Gravity and aeromagnetic data are used to interpret the location of basement features. The combination of these two, with unique corrections for the average relative location of each UOA with regard to surface and basement, is then used to derive a structural complexity score for each cell in each UOA. For example, the basement component is given more weight for the Frontier UOA than for the Lewis. The composite structural complexity score is assumed to correlate directly to the density of natural fractures. Figure 17 provides examples of these data for the Greater Green River basin.

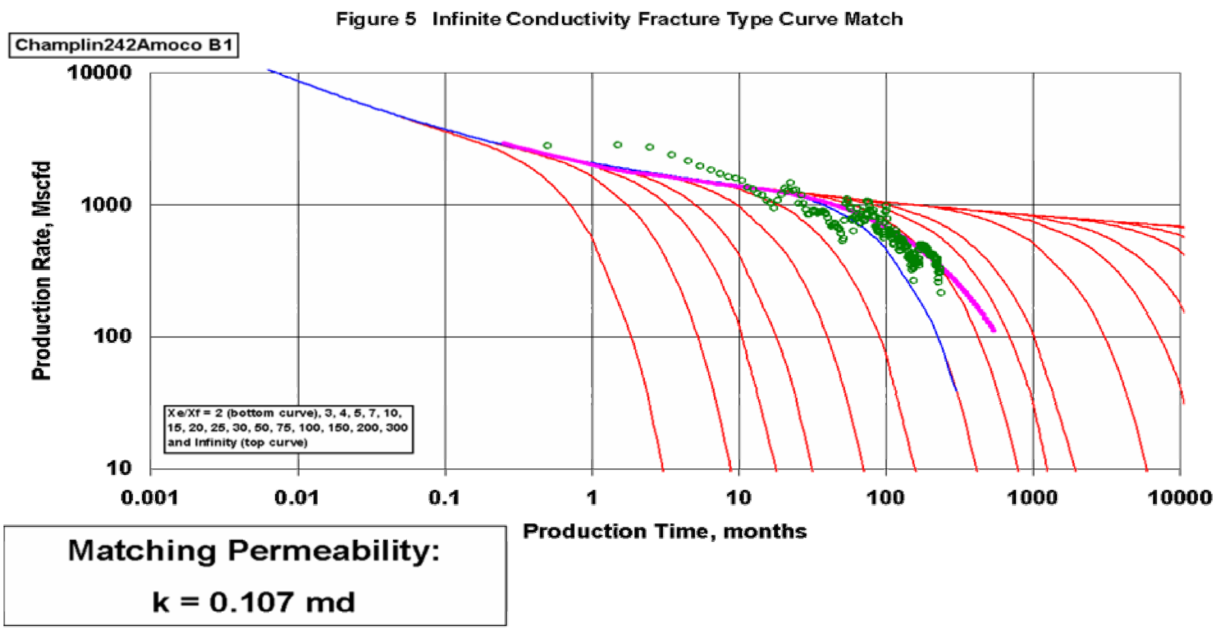

Figure 18: *Type curve match for the control well for Mesaverde UOAs in the Echo Springs field, eastern GGRB. Permeability assigned to this well (0.107 md) is assumed to be typical of the grid cell.*

Permeability Estimation in Control Data Sets: The general basis for estimation of permeability is the detailed analysis of productivity and log character for a typical well extracted from as many as 10 sample fields per UOA. For each type well, logs were analyzed to establish net completed pay, porosity, gas saturation, pressure and temperature. Production profiles were then matched to type curves to establish an estimate of effective permeability (Figure 18) that represents the sum of both matrix and fracture contributions

Permeability Estimation beyond Control Data Sets: As no production profiles exist in much of the appraised area, our approach to extending the prediction of effective permeability beyond the vicinity of the control wells was to separately estimate both the matrix and natural fracture components in each grid cell of each UOA. Determination of matrix permeability was determined by simply applying the best available correlation with estimated porosity. This correlation is one established for the Almond sands in the eastern GGRB by Cluff (2000).

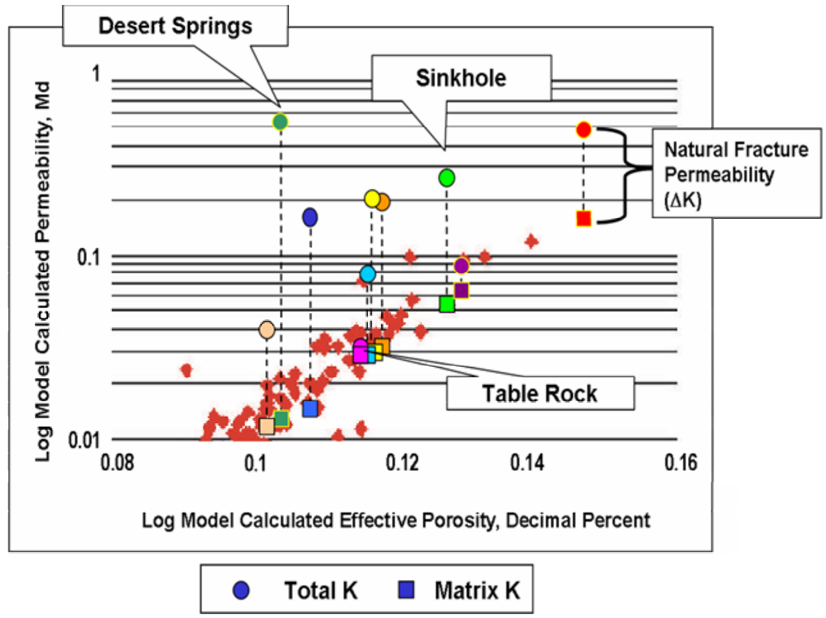

Figure 19: *Method for partitioning effective permeability into matrix and natural fracture overprint components. Example from the analysis of the Lewis UOA, GGRB.*

Establishing the natural fracture contribution to permeability for each cell was accomplished through correlation with observed structural complexity as follows. For each control well, expected matrix permeability (based on control well porosity and water saturation) was subtracted from the effective permeability estimate derived from type curve matching to determine the natural fracture contribution. In the example provided as Figure 19, type curve matching returned an estimated effective permeability of approximately 0.27 md for the Lewis UOA at Sinkhole Field. Based on analysis of logs from Sinkhole, 0.053 md of this total is interpreted to reflect matrix permeability. The remaining 0.217 md is therefore attributed to natural fracture overprint

Correlation of Fracture Permeability to Structural Complexity: Our methodology only has value if the estimates of structural complexity for the cells with control wells show a reasonable correlation to interpreted natural fracture permeability overprint. This test was conducted for the Lewis UOA (GGRB) and the Fort Union UOA (WRB). As shown in Figure 20, the correlation is respectable, and indicates the general utility of the methodology for the purposes of this study. That is, our method provides a reasonable approach to providing NETL's analytical models with realistic and areally-varying estimates of total effective permeability that recognize the contribution of natural fracturing. Clearly, however, this method does not have the resolution or accuracy to support the estimation of permeability at any given location, and is therefore not compatible with well siting.

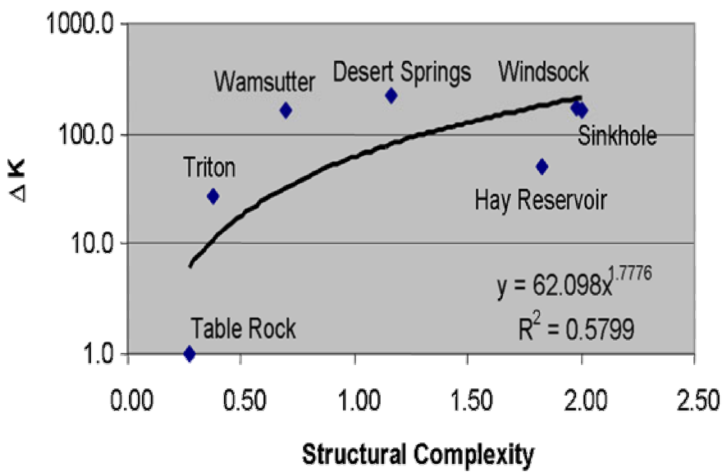

Figure 20: *Correlation of structural complexity and estimated natural fracture contribution to permeability (K) for 7 control fields in the analysis of the Lewis UOA. A similar comparison for the Fort Union UOA, WRB, found a similar correlation.*

Dataset Preparation

The purpose of this effort is to produce a dataset for input into NETL's Gas Systems Analysis Model that reflects, as much as practical, the natural variety present in key reservoir parameters. To do this, it is necessary to divide the resource into a large number of separate packets, with each packet having unique information on pay thickness, porosity, drilling depth, permeability, and other key factors. Therefore, a critical step in the creation of the model input datasets is the merger of the geologic data (collected relative to specific well locations) and the engineering data (collected relative to full or quarter townships) into a regular, cell-based, database.

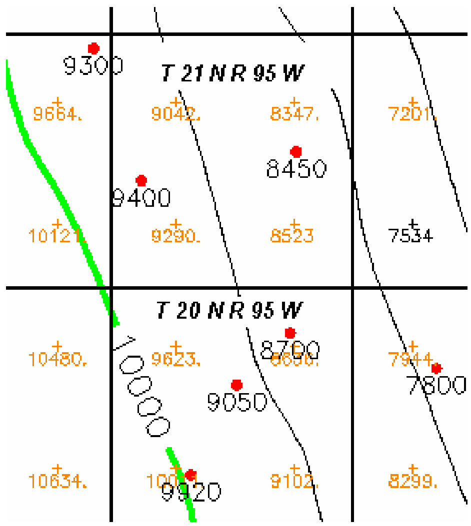

Figure 21: *An example of a gridded dataset – in this case drilling depths. Red dots are well locations. Orange values mark the centers of grid cells - in this example, cells are 9 mi^2 in size. Each cell is assigned a unique depth based on computer extrapolation of scattered well data.*

Figure 21 illustrates this process. The dataset of well-log-based values (red dots) is entered into computer software (EarthVision) and gridded (a typical first step in computer contouring programs in which values are interpolated at regular intervals from scattered data). To ensure that the program grids appropriately in areas of poor well control (and fills the entire play outline with data), roughly 20-40 "control" wells are created and added to the database for each UOA. These imaginary wells are placed along play boundaries, at the centers of interpreted structures, and in areas of poor well control in an effort to persuade the computer contours to match the geologic model.

The size of the grid cells used was 5,760 acres (equivalent to a quarter-township) for UOAs above the Cody Shale and 23,040 acres (full township size) for sub-Cody UOAs. Each volumetric parameter is gridded in this manner, producing a dataset that divides the entire resource into a large number of separate, and square, segments of equal size.

Finally, grid-cell level data were then converted into the specific format required for model input. Model input files were edited to remove grid cells that fall outside the play area and to ensure that the entire play area was gridded. In addition, all cells within the play area that have been drained by previous production were removed. In accounting for past production, our convention was to remove all cells from which existing wells had produced from the subject UOA in more than 25% of the available well locations. We believe this approach should provide a conservative estimate of remaining resources.

Distribution of Permeability within Grid Cells

The methodology described above was used to create a database characterizing roughly 8,000 unique resource packets, each with a unique combination of estimates for volumetric parameters, drilling depth, and matrix and effective permeability. Within each packet, therefore, a single characterization applies to all available drilling locations (equal to 36 160-acre locations per gird cell for UOAs above the Cody shale and 144 160-acre locations for those above – note that the.

current spacing assumption (160-acres) can easily be modified as later analyses require). Given the large number of cells, using a single average to represent these small numbers of locations clearly provides more than enough detail for our modeling purposes. However, with regard to permeability, further data manipulation was warranted for two reasons.

First, the permeability methodology is likely to have provided numbers that are not truly typical of the grid cell. They are typical of the control fields they represent, however, it is likely that those fields represent slightly better productivity than the remainder of the cell in which they reside. Also, the data quality necessary for type curve matching was found to be more common in better-producing wells. Second, and more importantly, permeability is not likely to be uniform across a grid cell. Although this is likewise true of the volumetric parameters, permeability is expected to deviate over a much larger range, and these deviations (small numbers of very good wells and large numbers of poorer wells) will have a much greater impact on modeled productivity and recoverability. Therefore, for the estimation of permeability, each cell was further divided into four unequal segments, with a modified effective permeability assigned to varying number of available well locations. For example, assume a cell in the Frontier UOA (a 36-mi^2 cell holding 144 possible 160-acre well locations) is assigned a permeability of 0.1 from the structural complexity analysis. For modeling purposes, this cell is broken into four cells of unequal size. Permeability is then assigned as illustrated in Figure 22, with the largest of sub-cell (holding 54 of the 160 available well locations) assigned a permeability equal to 30% of the original cell estimate and the smallest cell (holding 10 of the 144 well locations) assigned a permeability 3 times the original estimate.

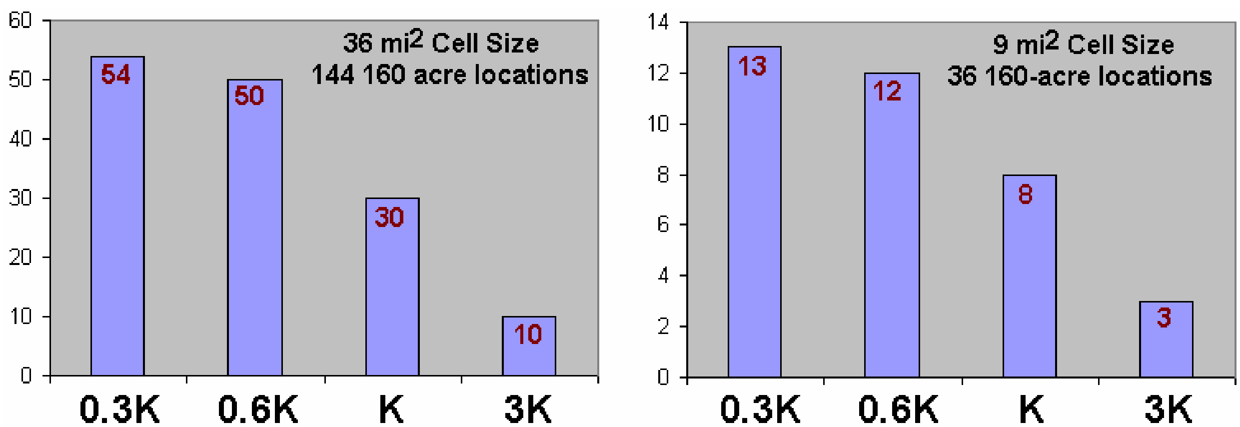

Figure 22: *Procedure for distributing a range of permeability within grid cells based on estimated average cell permeability.*

5. Results

The primary result of this work is the construction of detailed and disaggregated resource characterizations for major gas accumulations in the GGRB and WRB. These datasets, and the methodology that produced them, are specifically tailored to allow meaningful analyses of the relative impact of alternative future technology, cost, and policy scenarios using NETL's Gas Systems Analysis Model (GSAM). By compartmentalizing the resource both geographically and vertically into thousands of discreet packets, these datasets capture the natural variation in drilling depth, porosity, water saturation, pressure, temperature, and permeability that are necessary for meaningful modeling of specific technologies.

Figures 23 and 24 illustrate the improved detail of the new resource characterizations relative to those previously existing in NETLs models. Figure 23 shows the extent of improved aerial detail for the Lewis UOA, eastern GGRB. Whereas pre-existing datasets described the entire area of the Lewis gas resource relative to a single estimate for many parameters (such as drilling depth, pressure, temperature, and others), the new datasets divide the area into hundreds of uniquely-described segments. Figure 24 further illustrates this point of increased resolution with regard to the distribution of resource within each UOA. For example, whereas previous datasets for the GGRB placed all 159 Tcf assigned to the "Mesaverde Play" at a common depth of 15,000 feet,

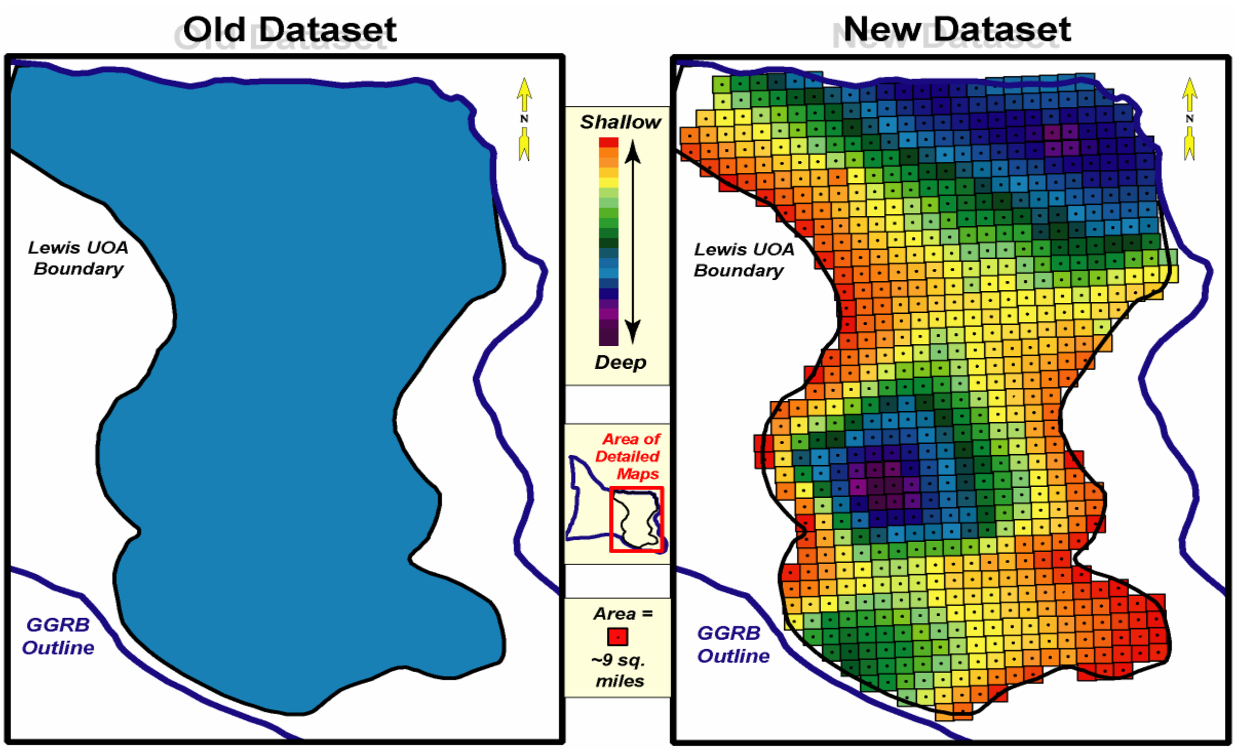

Figure 23: *Comparison of previously-existing NETL model characterization (left) with dataset prepared in this study (right) with regard to description of drilling depth. Example is from the Lewis UOA, GGRB.*

our new datasets divide more than 1,800 Tcf of in-place "Mesaverde" resource into three UOAs (Almond, Ericson, Lower Mesaverde), each with resources distributed in accordance with the true structure of the basin.

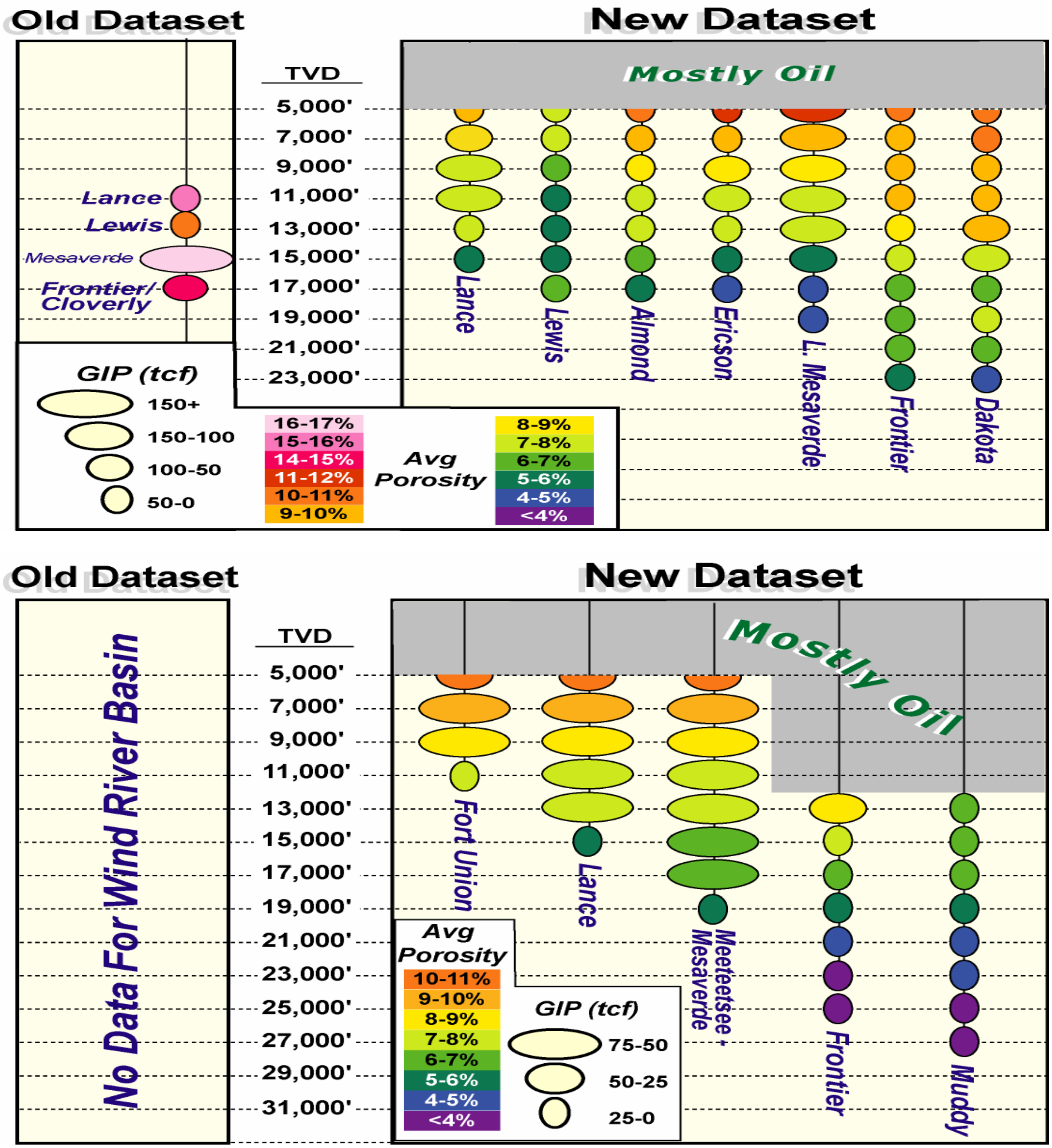

Figure 24: *Schematic comparisons of previous and new datasets relative to the distribution of resource with depth in 12 UOAs; Top – GGRB, Bottom – WRB. Previous datasets had less stratigraphic detail and placed all resources in each unit at a single depth. New datasets distribute depth among more units and across the full natural range of depth. Similar improvement is found relative to other parameters, including pressure, porosity, permeability, and water saturation. Note that previous datasets contained no Wind River basin resource.*

Volumetrics

The results of the volumetric analysis are summarized in Table 6 and Figure 25.

Table 6: *Gas-in-place and average volumetric parameters for GGRB and WRB UOAs. Average values refer only to the potential pay in each grid cell. For example, 7% porosity means that the average porosity of the zones identified as potential pay over all grid cells is 7%. Total values are the aggregate values for all grid cells.*

	Greater Green River Basin UOAs						
	Lance	**Lewis**	**Almond**	**Ericson**	**L. Msvd**	**Frontier**	**Dakota**
Area (thousands of acres)	5,247	4,332	8,363	8,484	9,066	11,128	11,796
Avg. Thickness (ft.)	341	82	27	119	305	46	55
Avg. Porosity (%)	8	7	9	9	8	8	8
Avg. Water Saturation (%)	58	61	62	53	58	39	35
Avg. Drilling Depth (Ft.)	8,628	10,104	9,882	9,729	10,778	14,511	14,629
Avg. Pressure (psi)	4,322	5,232	5,430	5,322	5,739	8,498	9,592
Avg. Temperature (^oF)	164	181	179	177	189	249	250
Avg. Z-Factor	0.99	1.05	1.03	1.06	1.06	1.39	1.40
In-place Resource (Tcf)	714	149	120	519	1,257	351	528
Resource below 15,000' (Tcf)	0.7	8	5	24	201	145	212
	Wind River Basin UOAs						
	F Union	**Lance**	**M-Mvd**	**Frontier**	**M-Lak**	**Nugget**	**Tensleep**
Area (thousands of acres)	1,094	1,267	1,480	1,613	1,866	1,682	1,247
Avg. Thickness (ft.)	408	560	524	135	53	76	285
Avg. Porosity (%)	10	9	8	6	6	5	6
Avg. Water Saturation (%)	56	50	42	41	35	*	*
Avg. Drilling Depth (Ft.)	8,240	10,003	12,021	18,931	20,058	19,485	20,458
Avg. Pressure (psi)	3,663	4,736	7,410	12,219	13,585	13,444	14,184
Avg. Temperature (^oF)	175	200	228	325	340	372	387
Avg. Z-Factor	0.94	1.03	1.16	1.52	1.52	1.57	1.61
In-place Resource (Tcf)	190	329	456	129	65	*	*
Resource below 15,000' (Tcf)	0	12	159	89	54		

**not estimated due to insufficient data*

The volume of gas present within each UOA was calculated on a per grid-cell basis. Average Z-factors were determined for each cell assuming 0.65 gravity pure methane gas using a modified form of Drunchak's equation coded into a Microsoft Excel function. In general, this study confirms past accounts of vast volumes of natural gas existing in these two basins (see Figure 25 for comparison to previous estimates). Specifically, we estimate approximately 4,800 Tcf of gas exists in-place within the appraised formations and areas of the Greater Green River (3,635 Tcf) and Wind River (1,169 Tcf) basins. The majority of this resource lies within the thick, dominantly fluvial sections of the Lance, Ericson, and Mesaverde UOAs of the GGRB and the Fort Union, Lance, Mesaverde-Meeteetsee UOAs of the WRB. Of this total, approximately 900 Tcf lies at depths below 15,000 feet. Figure 25 also compares the total gas-in-place estimates for

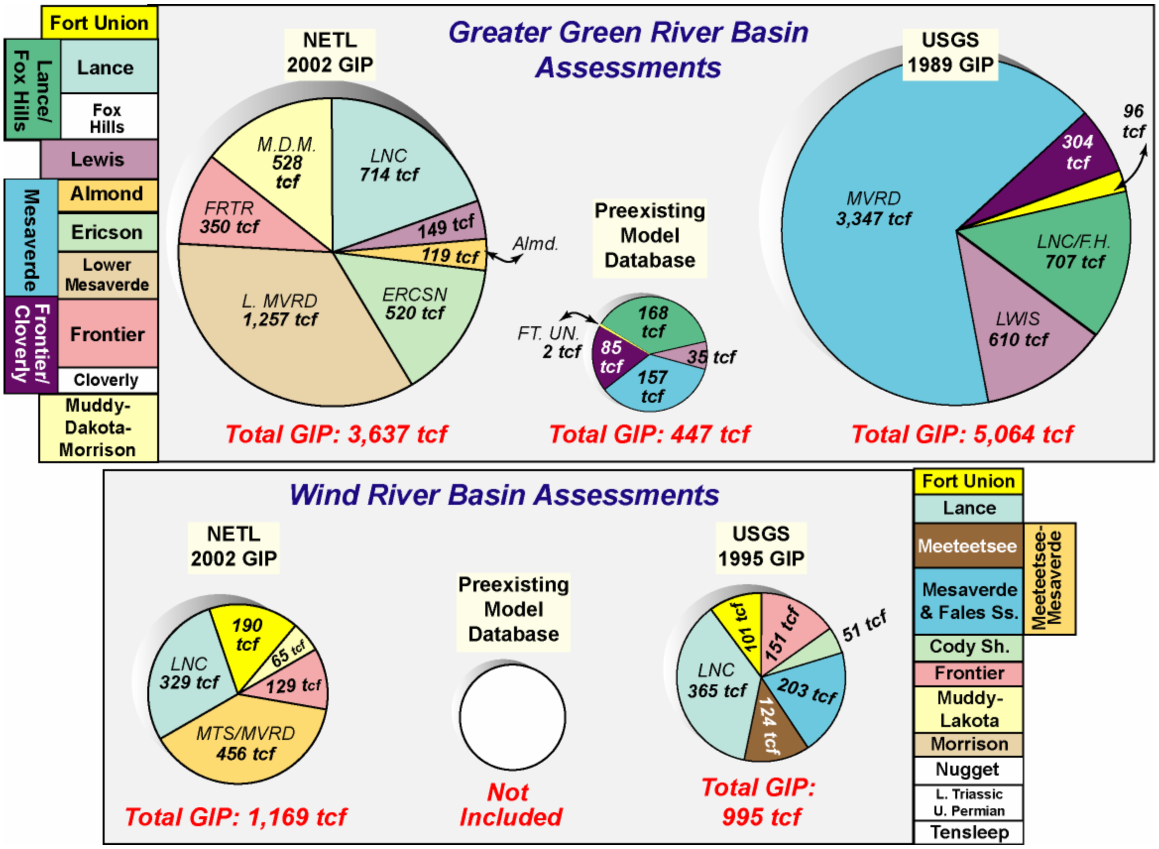

Figure 25: *Summary of the gas-in-place results of this study ("NETL 2002 GIP") with in-place resource characterizations previously available to NETL's analytical models databases and the findings of previous USGS gas-in-place studies (GGRB, 1989; WRB, 1995). Top: Results for the Greater Green River basin; Bottom: Results for the Wind River basin. Color keys to pies are provided. Pie size is proportional to total in-place resource.*

each UOA with the estimates previously utilized by NETL's analytical models for technology modeling. These previous estimates were based primarily on United States Geological Survey (USGS) estimates of technically-recoverable volumes from the 1995 National Assessment.

The volumetric results presented above present the sum total resource present in more than 8,000 separately-characterized resource segments, allowing the construction of histograms of the distribution of key volumetric parameters for representative UOA. Figure 26 provides some examples of these data - additional data are provided in charts and figures found separately on this CD. These distributions reveal the natural range and variety that exists for each of the critical parameters. For example, the left chart on Figure 26 shows the number of grid cells in the Lewis UOA, GGRB, that are assigned porosities in 1%-increments ranging from 4% to 20%. The plot shows a feature typical of many UOAs; values are not normally distributed around the average, but are instead slightly skewed to the lower values. The chart to the right, showing the distribution in potential pay thickness for the Fort Union UOA, Wind River basin, shows a similar skewing, as well as the common distribution of pay thickness across a large range (here nearly an order of magnitude).

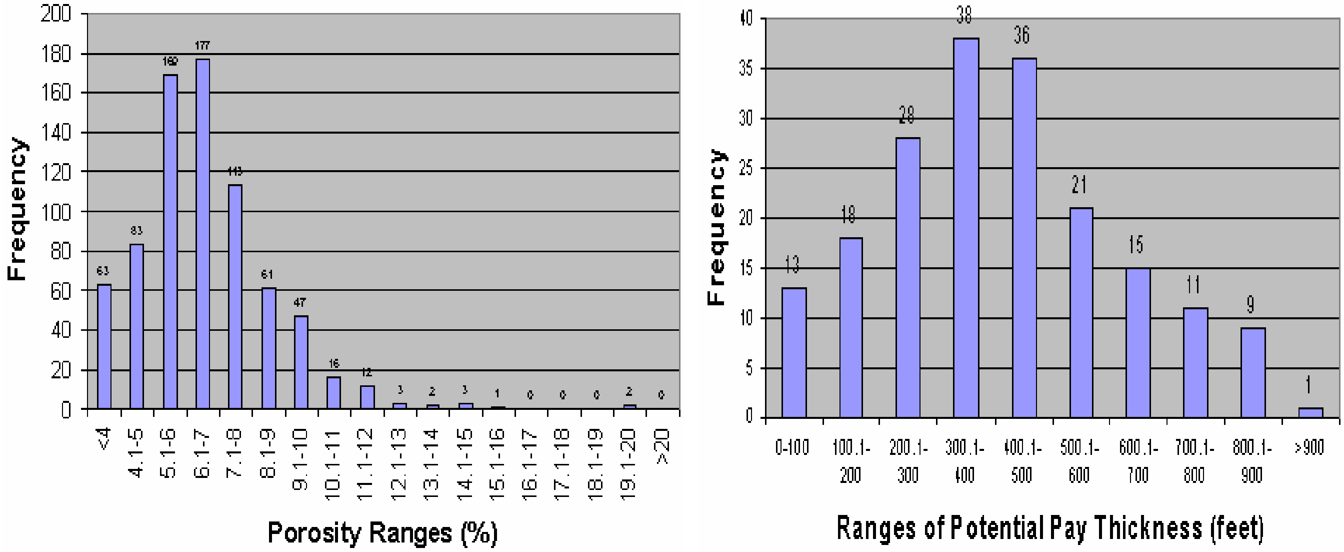

Figure 26: *Example histograms of volumetric parameters. Left – Histogram of potential pay thickness, Fort Union UOA, WRB. Right -Histogram of Porosity distribution in the Lewis UOA, GGRB.*

Resource Recoverability

Key to determining resource recoverability are our estimates of effective permeability. The distribution of estimated permeability shown in Figure 27 for the Lewis and Meeteetsee-Mesaverde UOAs are typical of those for all analyzed UOAs. Matrix permeability is commonly very low, less than 0.01 md, and often less than 0.001 md. However, total effective permeability spans a wide range. Values ranging upwards to 1 md (relatively rare) are present, with many cells assigned values in the range of 0.05 md.

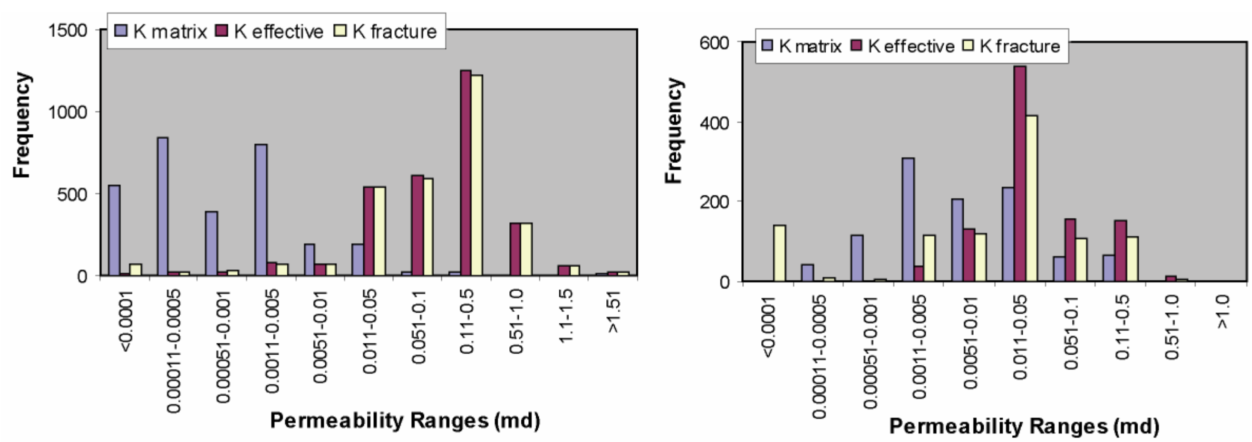

Figure 27: *Distribution of matrix, natural fracture, and total effective permeability in two representative UOAs. Frequency refers to the number of ¼-township grid cells. Left – data from the Lewis UOA, GGRB; Right – data for the Meeteetsee-Mesaverde UOA, WRB.*

Given the improved resource description and various input assumptions describing E&P technologies and costs, NETL's Gas Systems Analysis Model is used to estimate resource recoverability. GSAM's "technically-recoverable" resource is that portion of the in-place resource that can be extracted given current technologies and drilling practices without regard to price. GSAM also allows estimation of "economically-recoverable" resources through its assignment of a unique Minimum Acceptable Supply Price (MASP) to each resource segment (each grid cell in each UOA). The MASP is that price at which net present value for production of that resource equals zero (when long range production income balances costs at the assumed hurdle rate). Therefore, the economically-recoverable resource can be calculated for any given price, and will equal the sum of the technically-recoverable resources in all cells with MASP at or below that price. It should be noted, however, that the primary goal of GSAM is to estimate the *relative* merits of various alternative R&D approaches. Consequently, the absolute values for outputs such as recoverable resource for any particular case are not necessarily as meaningful as the magnitude and direction of change in these numbers between cases.

Table 7*: Selected base case components for GSAM analyses of the new GGRB and WRB datasets*

Parameter	*Marginal Marine UOAs*	*Basinal UOAs*	*Fluvial UOAs*	*Thick Fluvial UOAs*
Drilling Cost	*Set at JAS 2000 regional cost per foot relative to UOA drilling depth*			
Stimulation Efficiency	*60%: As this number increases, the cost of obtaining induced fractures of a given length decrease.*			
Operating/Maintenance Costs	*$8,963/well + $1.04/foot*			
Discount Rate	*25%: Represents the hurdle rate imposed on all projects by the operator.*			
Dry Hole Rate	*0%: As every cell presented to the model contains some gas, there are no truly dry holes, however - a vast majority of the cells in any reasonable case will be "dry" as they produce insufficient volumes to support drilling, completion, or operating costs.*			
Productivity (% of AOF)*	*25%*	*20%*	*20%*	*15%*
Skin Factor	*2*			
Induced Fracture Half-length	*300 feet*			
Induced Fracture Conductivity	*100 md-feet*			
Minimum System Pressure	*150 psi*			
Well Spacing	*160 acres*			
Recovery Factor	*50%*	*50%*	*20%*	*20%*

Explanation: Marginal-marine UOAs = Almond, Frontier-GGRB, Frontier- WRB; Basinal UOA = Lewis; Fluvial UOAs = Dakota-GGRB, Ericson-GGRB, Muddy-WRB; Thick Fluvial UOAs = Lance-GGRB, Lower Mesaverde, Fort Union, Lance-WRB, Meeteetsee-Mesaverde.

The results from GSAM, as from any model, are tied fully to the modeling assumptions incorporated into the "base case". In this study, the base case used reflects our attempt to represent current technology and costs. For the initial analyses of the GGRB and WRB datasets, we have produced a base case (Table 7) designed to capture the distinction between the expected drainage and productivity of 1) exceptionally thick fluvial UOAs (Lance, Lower Mesaverde, Fort Union, and Meeteetsee-Mesaverde), 2) thinner fluvial sections (Ericson, Dakota, Muddy), 3) marginal marine UOAs (Almond, Frontier) and 4) basinal UOAs (Lewis). Two model levers were used in creating this distinction. The first lever is a "productivity" parameter in GSAM that controls the percentage of calculated absolute open flow that will be produced. This lever is intended to account for various factors, including well flow restriction and less than full completion of the total available pay. The lever is set at lower values for thicker units to recognize the fact that lesser portions of the total available pay are likely to be completed. The second lever accounts for variations in recovery efficiency (the % of the spacing area to be drained) and recognizes the inherently higher lenticularity of fluvial units.

Table 8 provides GSAMs estimates of base case technically-recoverable resources for each UOA as calculated by GSAM. Note that the Nugget and Tensleep UOAs in the Wind River basin were not analyzed due to lack of sufficient data. The estimates for base case economically-recoverable resources at $2.00/mcf and $3.50/mcf gas prices are also presented.

Table 8: *GSAM estimates of technically and economically-recoverable resources in each UOA. Values in Tcf.*

Greater Green River Basin				***Wind River Basin***			
UOA	*Technically-Recoverable*	*Economic @ $3.50*	*Economic @ $2.00*	*UOA*	*Technically-Recoverable*	*Economic @ $3.50*	*Economic @ $2.00*
Lance	68	46	18	*Fort Union*	18	10	4
Lewis	33	18	12	*Lance*	29	11	5
Almond	27	8	3	*Meet.-Mvrd.*	37	9	2
Ericson	44	11	4	*Frontier*	32	3	<1
L.Mesaverde	95	21	6	*Muddy*	6	<1	<1
Frontier	59	<1	<1				
Dakota	37	1	<1				
TOTAL	**363**	**105**	**43**	***TOTAL***	**122**	**33**	**12**

GSAM's estimates of 363 Tcf technically-recoverable and 105 Tcf economically-recoverable (at $3.50/mcf price) for the Greater Green River basin significantly exceed the estimates of the USGS in association with the 1995 National Assessment (119 technically-recoverable and 3.3 Tcf economically-recoverable at $3.34/mcf gas price). A 2002 update by the USGS has further reduced the GGRB estimate to 82 Tcf of technically recoverable resource. The differences stem from employing alternative methodologies, different geologic models, and different assumptions. The fact that USGS produces a more conservative answer than our methodology is to be expected when the methodologies are compared. USGS estimates for continuous-type plays are based on the extrapolation of past production history to that play's remaining untested regions and therefore, is influenced by the past economic decisions of operators. These decisions include what technologies to use, whether to complete the well and in what zones, and when to shut-in. In contrast, GSAM's estimate of technically recoverable resource is based on the fundamental reservoir geology modeled under current technology conditions and assuming full resource development. Nonetheless, the GSAM estimate does recognize the practical limits of technical recoverability by including factors that limit recovery factor and productivity (see Table 7.)

Technology Sensitivities

These new characterizations of marginal and sub-economic gas resources were completed primarily to help assess the relative potential of alternative R&D approaches to improve the resource's technical and economic recoverability. Consequently, the most significant outcome of these GSAM analyses is the indication that the resource recoverability is not fixed, but is instead very highly sensitive to changes in both technology and economic conditions. Figure 28

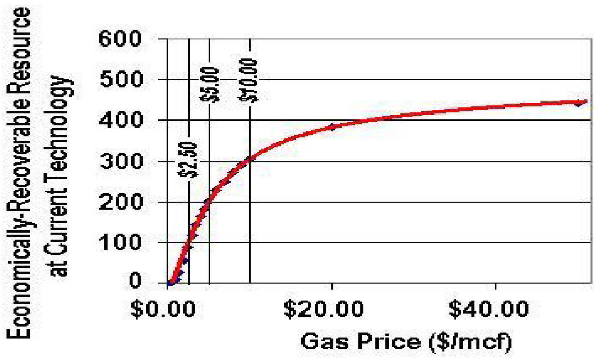

Figure 28: *Economically-recoverable resource versus gas price for the GGRB and WRB datasets*

shows how economically-recoverable resource varies with gas-price. For example, at a wellhead gas price of $2.50/mcf, 89 Tcf of the assessed resource in the GGRB and WRB is economic; however, this volume more than doubles to nearly 200 Tcf at a price of $5.00/mcf. This sensitivity to price clearly translates directly into sensitivity to technology advance. Figure 29 details the sensitivity of the economically-recoverable resource to potential changes in six representative GSAM technology/cost parameters. For example, GSAM predicts the addition of roughly 15 Tcf to the economically-recoverable resource (at $3.50/mcf price) for every 10% reduction in drilling costs. Similarly, each 10% improvement in stimulation cost efficiency adds approximately 8 Tcf to economically-recoverable volumes. These findings indicate that realistic technology advance can have a profound impact on the future recoverability of these resources.

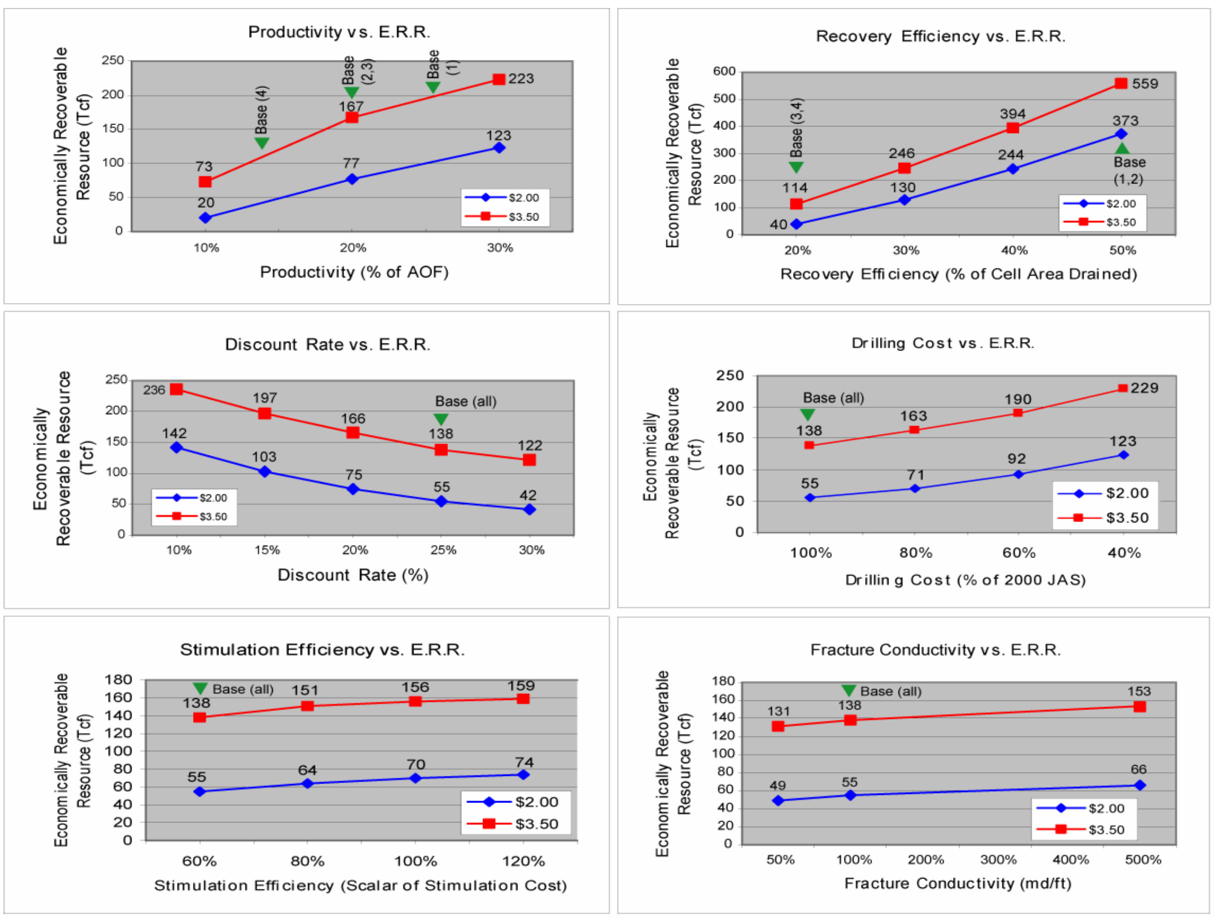

Figure 29: *Sensitivity of GSAM estimates of economically-recoverable resources to incremental changes in key model parameters that are used to represent technology advance. The green triangles indicate the settings for these values for unique portions of the base case ("1" = marginal marine UOAs, "2" = basinal UOAs, "3" = fluvial UOAs, and "4" = thick fluvial UOAs.*

Distribution of Gas-in-Place Resource Relative to Federal Land Access Stipulations in the GGRB.

This study provides a detailed geographic depiction of natural gas resources in the Greater Green River and Wind River basins. In addition to supporting the modeling of technologies, this detail provides an opportunity to assess fully the distribution of resources relative to various classes of Federal land access.

To accomplish this, NETL's work on resources has taken advantage of the results of an ongoing inventory of Greater Green River basin federal land access stipulations being conducted pursuant to the Energy Policy and Conservation Act (EPCA) Amendments of 2000. The study is being performed by Advanced Resources International (ARI) for the EPCA Interagency Team that which includes the Department of Interior (Bureau of Land Management, U.S. Geological Survey), Department of Agriculture (Forest Service), and Department of Energy (Energy Information Agency and Office of Fossil Energy). For each grid cell in each UOA of the GGRB, we have determined the percentage of gas-in-place resource that falls within four Federal leasing and land use categories, as follows (Figure 30):

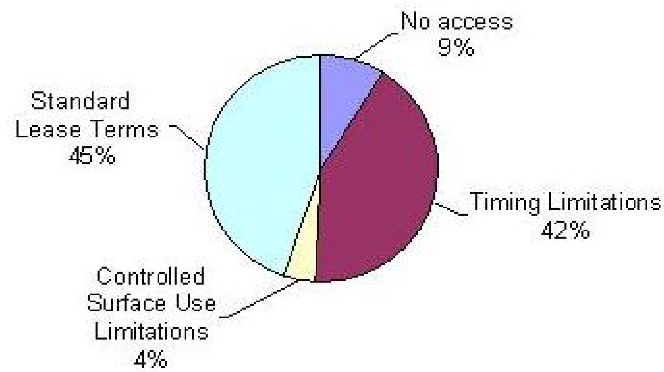

Figure 30: *Distribution of gas-in-place in 6 GGRB UOAs relative to four categories of federal land access restriction.*

- ***No Access to Resources*** includes four EPCA access categories: (1) no leasing due to statutory or executive order restrictions; (2) no leasing, due to land pending use planning actions; (3) no leasing, due to local (administrative) restrictions; and (4) leasing allowed, but surface occupancy restrictions make access impractical

  Under current legislation or land use plans, these Federal Land areas are "off limits" to oil and gas development. Changes to portions of these land use categories may occur over time, but no reliable means exists on how to forecast this on a township/play level basis.

  Future updates of EPCA would provide new information that would be incorporated to update the NETL database on Federal land use and access. Sensitivity runs with GSAM could be used to examine policies or technology that would relax the no leasing or access constraint.

- ***Leasing, with Drilling/Development Timing Limitations*** also contains four EPCA access categories:

  - Drilling limitations of 9 months, an extremely small category.
  - Drilling limitations of 6 to 9 months, a moderate size category.
  - Drilling limitations of 3 to 6 months, the largest and dominant category.

– Drilling limitations of less than 3 months, a very small category.

Assessing the impact of this category of restrictions is complicated by the fact that, about 40% of the time, drilling limitations can be waived to expand the drilling time window. However, on average, lands falling within these categories are available for drilling only 8 months of the year. This restriction has significant implications for reducing the pace of development and adds costs for extra rig-move or stand-by time.

- ***Leasing, with Controlled Surface Use Restrictions*** is an EPCA Federal land use category that represents stipulations that add significant costs in addition to those existing under standard leasing terms.

- ***Leasing, Standard Lease Terms.*** These Federal lands contain standard lease terms which impose significant costs for environmental compliance.

The gas resources in each Federal land use category were summed to determine the total gas-in-place resource present by stipulation category. The results (Figure 26) show about half (45%) of the total gas-in-place in the GGRB is available under standard lease stipulations. Of the 55% of resource carrying restrictions, 42% are timing restrictions, 4% are controlled surface usage stipulations, and 9% are resources that are restricted from leasing.

Table 9*: Gas resources relative to four categories of land access for six GGRB UOAs.*

UOA	No Access	Timing Limitations	Controlled Surface Use Limitations	Standard Lease Terms
Lewis	7% (10 Tcf)	36% (54 Tcf)	5% (7 Tcf)	52% (77 Tcf)
Almond	11% (12 Tcf)	38% (42 Tcf)	7% (8 Tcf)	44% (49 Tcf)
Ericson	9% (45 Tcf)	45% (233 Tcf)	3% (16 Tcf)	43% (221 Tcf)
Lower Mesaverde	11% (134 Tcf)	40% (494 Tcf)	4% (45 Tcf)	46% (570 Tcf)
Frontier	7% (22 Tcf)	49% (164 Tcf)	3% (9 Tcf)	41% (138 Tcf)
Dakota	8% (37 Tcf)	45% (217 Tcf)	4% (19 Tcf)	43% (209 Tcf)

Table 9 provides this information at the UOA scale, showing the variation in percentages that reflect the differences in the distribution of resource among various geologic units. For example, resources in the Lewis UOA, located exclusively in the eastern half of the basin, show significantly less restriction that those of other plays with wider geographic distribution.

Next Steps

Our analyses indicate that approximately 4,800 Tcf of natural gas exists in-place in the subject intervals of the Greater Green River and Wind River basins. Going forward, this resource characterization will be subjected to numerous analyses using NETL's analytical models to determine how recoverability of this resource relates to various scenarios of future technological progress. In addition, NETL will continue to support efforts that analyze the impact of federal land access stipulations, recognizing the potential of future technology/cost/policy scenarios to significantly expand the technical and economic recoverability of this resource.

In October, 2002, NETL kicked off Phase II of this effort, consisting of similar resource characterization studies of the marginal and sub-economic resources of the Anadarko (Oklahoma-Texas) and Uinta (Utah) basins.